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Current and future economic performance of first and second generation biofuels in developing countries

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HIGHLIGHTS

- First generation biofuels have a cost range of 5–45 $/GJ for all settings considered in this study.
- Second generation biofuels have a cost range of 14–26 $/GJ for all settings considered in this study.
- There is higher uncertainty in cost estimates for second than first generation biofuels.
- Key cost factors are labour costs, agricultural efficiency, biomass yields and conversion costs.
- Acquiring location specific data is essential for accurate cost estimation.

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ABSTRACT

Net Present Value (NPV) and total production cost calculations are made for first and second generation biofuels in 74 settings, covering 5 fuel output types, 8 feedstock types, 12 countries and 8 combinations of agricultural management systems between 2010 and 2030. Yields are assumed to increase due to better crop management and improved varieties. High NPVs (meaning profitable production) are calculated for cassava (up to 16,000 $/ha) and palm production (up to almost 7000 $/ha). But cassava can also have a negative NPV which indicates that the project investment is not without risk. The calculated NPVs for jatropha range from −900 to 2000 $/ha, while for sugarcane and soy the NPV is always positive, (2500–5000 $/ha and 200–3000 $/ha respectively) and therefore profitable. Total production costs in 2010 are estimated to vary from 5 to 45 $/GJ for 1st generation feedstocks in 2010, and from around 10–35 $/GJ in 2020, compared to 20–30 $/GJ for fossil fuels. Argentina and Malaysia are the regions with the lowest production costs for biofuel (soy and palm biodiesel for 11–15 $/GJ and 8–23 $/GJ respectively), although potential for cost reduction exists in other regions. Production costs of 2nd generation biofuels are estimated to be 17–26 $/GJ in 2020 and 14–23 $/GJ in 2030. Poplar based synfuel production in Ukraine has the lowest costs (14–17 $/GJ) and rice straw based bioethanol the highest (23–26 $/GJ) – for both the short and long term. The time between investment and benefits, as well as the size of investment and the alternative commodity markets, varies with the type of feedstock. The choice of feedstock therefore depends on the local agricultural system, and the preferences and means of the local farmers. Key to the competitive production of 2nd generation fuels is the optimisation of the conversion process, which dominates overall production costs (with 35–65% of total costs). Also important is the efficient organisation of supply chain logistics, especially for the low energy density feedstocks such as wheat straw – requires densification early in the chain. Key factors in the economic analysis are: labour costs and requirements, agricultural efficiency, conversion cost and biomass yields. Acquiring accurate location specific data is essential for detailed analyses.

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1. Introduction

Climate change is at the top of the political agenda and negotiations are ongoing in order to set an international policy framework in a post-Kyoto era, where developing countries are expected to play an increasing role in global climate change mitigation. Biofuels offer a large potential to displace petroleum fuels in transport and some stationary applications, with the promise to decrease global greenhouse gas (GHG) emissions [1–3]. Furthermore, biofuels can provide other local and regional benefits such as energy security, rural development, positive impacts on (regional)

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gross domestic product (GDP), and mitigation of local pollutant emissions [4–8]. The main drivers for the deployment of biofuels include:

1. Contribution to energy security by diversifying energy supply sources, increasing the number of energy producing countries and a potential to supply 'homegrown' energy;
2. Potential to contribute to GHG emission reduction targets by replacing fossil fuels;
3. Potential to contribute to development, with special focus on rural development, revalorization of rural areas and improving access to modern energy services [1,9,10].

Moreover, increasing energy prices, particularly of oil, are also stimulating the market for alternative energy sources, and bioenergy appears to be increasingly competitive in developing countries, due to suitable climate conditions, comparatively large available/unutilised land areas and relatively low biomass production costs [4,11]. However, increasing concerns have been expressed with regard to the sustainability profile of biofuels [12]. Frequently cited issues of concern include potential negative environmental impacts due to biomass production and social conflicts that could result from potential food versus fuel competition, but critics also point to potential economic unsustainability of some biofuel pathways [1,13]. Various studies have analysed environmental impacts of biofuels production (e.g. GHG emissions by Hoefnagels et al. [14] and by Muench and Guenther [15]) and social effects in developing countries (e.g. [7,9]. These studies show that biofuel production impacts vary greatly from country to country and that some production and supply pathways, practices and technologies are more sustainable than others. The impacts of bioenergy projects in developing countries depend, among others, on the natural conditions (climate, soil), on the socio-economic setting (employment, poverty, governance) and especially on the feedstock production system that is used (crop type, agricultural management system) [8,16,17]. To effectively evaluate key biofuel production and supply impacts, detailed environmental and socio-economic datasets are required [18] . However, detailed data availability is problematic for developing countries. Also, studies that look at economic sustainability of biofuel value chains, typically focus on one specific region (e.g. Africa), or on one specific agricultural management system type (e.g. smallholders) [19–21], and usually this does not account for the large variety in sustainable biofuel production options. Therefore, the objectives of this study are to compile data sets for biofuel production in developing countries, and to analyse the corresponding economic performance of biofuel supply chains taking large variations between feedstocks and countries into account. Economic evaluation of biofuel production include a detailed analysis of the viability of feedstock production (in terms of Net Present Value (NPV) and the total production costs including conversion, transport and distribution.

Sustainability of biofuels production in terms of financial feasibility, depends (amongst others) on the specific local context, the type of business model that is used, and the type of feedstock [21]. For feedstock production, nearly all steps can be realised with different processes, intensity and efficiency, land use patterns, etc. and under very different social and economic circumstances. To assess the impacts of biofuel feedstock production, key variables considered include the biofuel type produced, feedstock used, soil characteristics and climate conditions where production occurs, the agricultural management system employed, socio-economic conditions (e.g. cost of labour, land and fuels, (un)employment rate, availability of land for energy crop production, ownership of land), among other factors. For the entire biofuel supply chain, there is a multitude of production pathways that include agricultural and forestry production and harvesting systems, downstream conversion routes as well as fuel and material inputs and associated many intermediate logistic operations.

The feedstocks that are selected include the most commonly used in developing countries (e.g. sugarcane and palm oil) for "first generation" biofuel production and some of the most promising ones (e.g. switchgrass, organic residues) for "second generation" biofuels production [22,23]. Currently, more than 99% of all currently produced biofuels are classified as "first generation" (i.e. fuels produced primarily from cereals, grains, sugar crops and oil seeds) [24,25]. "Second generation" or "next generation" biofuels, on the other hand, are produced from lignocellulosic feedstocks such as agricultural and forest residues, as well as purpose-grown energy crops such as vegetative grasses and short rotation forests (SRFs) [1,22]. Further definition of the scope of the study is given under description of the setting in the methodology section.

This paper is structured as follows: Section 2 explains the methodology and the 'setting' approach, while in Section 3 the results of the economic analysis is provided. In Section 4 the results are discussed and Section 5 finalises with the conclusion and recommendations. Detailed input data and key assumptions are provided in the Appendix.

2. Approach and methodology

2.1. Settings

To take into account the broad variety of biofuel production and supply pathways, a so-called setting approach was developed whereby several variables are combined into 74 different settings. A "Setting" is a combination of biofuel production and supply chains ("life-cycles") with similar typical socioeconomic (e.g. ownership structure, intensity and scale of production) and environmental (geo- and biophysical, climatic) characteristics. The variables that are considered in this study include biofuel produced, feedstock input, geographical scope (region), crop management system and time frame as discussed below.

Fuel output – All liquid fuels that have reasonably large market shares are considered (i.e.):

- VO (Straight Vegetable Oil).
- Biodiesel, 1st generation FAME (Fatty-acid methyl ester).
- Biodiesel, 2nd generation BTL (Biomass-to-Liquid).
- Ethanol, 1st generation (EtOH).
- Ethanol, 2nd generation (enzyme-enhanced lignocellulose conversion) (next EtOH).

Other fuels such as bio-butanol, bio-methane and bio-electricity are not considered in this analysis, because of their limited current market share and experience.

Time frame: Three timeframes are included; for 1st generation biofuels we evaluate the sustainability performance in 2010 and 2020, and for 2nd generation biofuels the assessment was for 2020 and 2030 (since commercialisation of 2nd generation technologies is expected in the next decade [8]. For analysis to 2020 and 2030, the projections take into account yield and cost developments as discussed in Sections 2.2 and 2.3.

Feedstock input: The selection of feedstocks that are analysed reflects a balance between including a representative list of common and promising feedstocks suitable for the different developing geographical regions, and maintaining a manageable number of settings. The following feedstocks (with reference – between parentheses – to the liquid fuels they are converted to) were selected:

- Sugarcane (1st and 2nd generation EtOH).
- Cassava (EtOH).
- Oil palm (FAME, SVO).

- Energy grass (next EtOH, BtL).
- Soy (FAME, SVO).
- SRC-short rotation coppice (BtL, next EtOH).
- Jatropha (FAME, SVO).
- Organic residues including wheat and rice straw (next EtOH).

Some potential biofuel feedstocks are worth mentioning, such as maize, rapeseed, sweet sorghum, pongamia, castor, cotton, and sunflower. These were not selected because their current market share in biofuel production in developing countries is limited and data availability for other crops such as sweet sorghum is poor [13,22]. Furthermore, crop such as maize are contentious and typically not considered as fuel feedstock for developing countries [9] (although this practice is prevalent in the United States) [25]. Other crops such as rapeseed are only produced in the European Union.

Geographical scope: The selected combinations of feedstocks and geographical coverage are listed in Table 1 and is representative of the multitude of potential settings for developing countries. Often several agro-ecological zones and socio-economic conditions exist in a given country (the former is differentiated through productive and marginal land suitability classification and associated energy crop yield levels). Details on the specific regions that are selected are provided in the results section and also in the Appendix.

Crop management system/cultivation: The agricultural management systems selected in this analysis are feedstock specific. Three different management systems (based on the level of input intensity, mechanization and tillage practice) are selected and assessed as follows:

(a) *Level of input intensity (low inputs/intermediate inputs/high inputs):* The input level intensity relates to the level of agricultural technology employed in feedstock production such as amount of fertilizer and chemical inputs. It influences the labour requirements for feedstock production, affecting total input expenses and ultimately biomass yields. Input levels apply to the activities in feedstock production, from land preparation, cultivation to post-harvest activities such as storing or packing (based on [21,26]) Table 2 provides an overview of the different activities that are included per input level. Detailed data on input levels such as typical quantities of fertiliser and pesticides use are given in Appendix B.

(b) *Low level of mechanisation/high level of mechanisation/no mechanisation:* The level of mechanisation refers to the degree to which machinery is employed in feedstock production activities in contrast to employing labour. Depending on the cost of labour and investment in machinery, degree of mechanization influences feedstock production expenses (i.e. field clearing, field preparation, planting, weed control, fertilisation, etc.) and also has socio-economic impacts by reducing the requirements for (unskilled) labour. In the context of developing countries, we distinguish in this study between labour intensive operations (no mechanization), a common level of mechanisation (referred to as 'low level') and a level of mechanisation that can be realised in the future (referred to as 'high level' – this level is comparable to mechanization levels in developed countries). These different levels of mechanization are defined by the type of equipment used for each of the feedstock production activities as well as application of irrigation. This has impacts on production inputs (such as fuel), labour requirements and biomass yields.

(c) *Tillage/no tillage:* The use of no-tillage or reduced tillage leads to better environmental performance through lower carbon and water footprint compared to the more conventional system of tillage. No tillage decreases soil erosion compared to repeated tillage, as there is a decrease in disturbance of the soil structure, furthermore there is an improvement of the physical and hydrological properties of the soil [27]. The tillage system has an impact on the amount of residues that can be removed from the fields and soil water retention, and thus affect crop yields. Also the amount of chemical fertilisers and herbicides applied depends on the type of tillage practice [28–30]. The use of no-tillage is currently the most common practice in Argentina and is therefore incorporated in the settings that relate to Argentina (soy and switchgrass) [27].

2.1.1. Overview

The matrix of 5 fuel types, 8 feedstock types, 12 geographical areas, 8 combinations of crop management/cultivation systems and 3 time frames would result in 11,520 different settings. We limited the combinations to 74 representative settings, that include key feedstocks and their respective major production

Table 1
Matrix of selected countries and feedstock combinations.

	Soy	Sugarcane	Oil palm	Jatropha	Cassava	Energy grass	SRC	Residues
Africa								
Mali				✓				
Mozambique		✓			✓		✓[a]	
Tanzania				✓	✓			
Americas								
Argentina	✓					✓[b]		
Brazil		✓					✓[a]	
Colombia			✓					
Asia								
China								✓[e]
India				✓				
Indonesia			✓					
Malaysia			✓					
Thailand					✓			
Europe								
Ukraine							✓[c]	✓[d]

[a] Eucalyptus.
[b] Switchgrass.
[c] Poplar.
[d] Wheat straw.
[e] Rice straw.

Table 2
Matrix of crop management activities by level of inputs.

	Field clearing	Filed preparation	Planting	Weed control	Pruning	Fertilisation	Pest and disease control	Irrigation	Harvesting	Post harvest activities
Low inputs	●	●	●	●					●	●
Intermediate inputs	●	●	●	●	●	●	●		●	●
High inputs	●	●	●	●●	●	●●	●●	●	●	●

•• indicates a higher level of intensity.

Table 3
Selection of representative settings by feedstock type.

Feedstock	Fuel	Time frames	Geographical areas	Crop management systems	Number of settings
Sugar cane	EtOH	2	2	2	8
	next EtOH	2	1	1	2
Palm oil	FAME	2	3	2	6
	SVO	1	1	1	1
Soy	FAME	2	1	3	6
	SVO	1	1	1	1
Jatropha	FAME	2	3	13	16
	SVO	1	1	1	1
Cassava	EtOH	2	3	3	15
SRC	next EtOH	2	2	1	6
	BTL	2	1	1	4
Energy grass	next EtOH	2	1	1	2
	BTL	2	1	1	2
Organic residues	next EtOH	2	2	1	4
Total					74

regions together with selected agricultural management level, as shown in Table 3. A detailed description of all settings is presented in Table A1 in Appendix A.

2.2. Investment appraisal – NPV

Because costs and revenues occur at different points in time, and because the value of money changes during time, the Net Present Value (NPV) is calculated in order to enable a comparison between the different feedstocks. All future costs and revenues of feedstock production are transformed to their present values, which are then summed up and result in an overall net positive, negative or neutral result. This is done to show the profitability of the crop for the farmers, and is only performed for first generation feedstocks.

For 2nd generation feedstocks, only the production costs are analysed since the market values of the feedstocks are not known due to the little experience with these type of biofuels so far. Furthermore, part of the feedstocks for 2nd generation are based on residues whose market value is not known since residue markets are not yet developed in many countries. For example, in South Africa, it is difficult to determine the true price of residues for animal uses[1] since the residues are typically traded informally [31]. Also, there is little commercial production experience in developing countries of energy crops such as switchgrass and thus their market value is not known. Therefore the crops for which already experience exist (mainly first generation) are analysed by using the NPV methodology (so costs and benefits), while the other crops (mainly 2nd generation) are analysed by calculating only the production costs.

The costs that are taken into account include all expenses from land preparation to harvesting of biomass, incorporating both labour and material expenses such as land rent, fertiliser, herbicides, other supplies, and machinery. The benefits are calculated by multiplying the yield and the market price for the raw biomass. This means the NPV is calculated from a farmer's perspective and not for example from the processor's perspective. The NPV is calculated using the following formula (based on [21]:

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i} \tag{1}$$

were NPV is the Net Present Value ($); B_i the benefits in year i ($); C_i the cost in year i ($); r the discount rate (%) and n the lifetime of project (years).

The NPV will increase, if costs are reduced (inputs of fertilizers, labour, energy, etc.) and/or if the benefits are increased by higher market prices or an increased yield. The discount rate used is the real discount rate, or long term lending rate taking into account inflation (see [21] for the formula[2]). The discount factor that is used is 8% based on [21]. This rate, applies to many countries in our analysis: Tanzania, Mozambique, Mali and Thailand, and is assumed to be the same for the other selected regions. The discount rate for some countries varies slightly from this value, Colombia for example has a discount rate of 10% [32]. Therefore in the sensitivity analysis, the discount rate is varied from 6% to 15%.

For the crops that include 2010 as timeframe (mostly first generation), cost and benefits based on actual costs and prices are used, using literature. The literature is supported by primary data collected in Mozambique, Ukraine, Argentina, Tanzania and Thailand. The costs and benefits for the timeframes 2020 and 2030 are extrapolated based on literature and expert knowledge.

In Appendix B, detailed input data including all expenses and revenues that are taken into account, is provided per feedstock. All $ are US$ 2010, and the economic lifetime of perennial plantations is assumed to be 24 years (based on [33]).

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[1] Maize stover is used as animal fodder during winter in South Africa when the quality of pastures is poor.

[2] Example: If the inflation rate is 10% and the long term lending rate 16%, the real discount rate is 6.

In general, a positive NPV indicates potential profitability. If the NPV is close to zero (no-profit no loss), then the financial viability of the project could be further researched using an extended Cost Benefit Analysis. The NPV is calculated using one default revenue value (an average) for the fresh products (raw feedstock). The feedstocks can be used for different markets (food, fuel, fodder), furthermore, market prices are volatile, and yields can vary per year. Therefore, as part of a sensitivity analysis, a range in market price values is included to analyse the robustness of the NPV. When evaluating the economic performance of the biomass production, not only the NPV of the feedstock/project itself should be taken into consideration, but also the performance must be compared to similar feedstocks or projects undertaken in a specific region. Depending on the outcome of the comparison it might be advisable to switch to a different feedstock or technology that is more profitable. Or, on the other hand, if opportunity costs in the region are close to zero, even low NPVs (a few hundred $/ha) could make investment worthwhile.

2.3. Total production cost

The total production cost includes feedstock costs (including labour, fertilizers, etc.), transport costs (from field to conversion plant), conversion and refining costs, and distribution to the end consumer (filling station). Feedstock production costs are calculated by dividing the total discounted costs by the total discounted yields, using the following formula [21,34]:

$$C = \frac{\sum_{i=1}^{i_t}\left(\mathrm{ecc}_i\sum_{y=1}^{n}\frac{f_i(y)}{(1+r)^y}\right)}{\mathrm{yld}\sum_{y=1}^{n}\frac{f_{\mathrm{yld}}(y)}{(1+r)^y}} \tag{2}$$

where C is the cost of biomass (\$ t^{-1}); it the number of cost items with different time pattern; ecci the cost of energy crop cost item (\$ ha^{-1}); n the number of years of plantation lifetime (yr); $f_i(y)$ the number of times that cost item i is applied on the plantation in year y [dimensionless]; r the discount rate (%); yld the yield of the energy crop (t ha^{-1} yr^{-1}) and $f_{\mathrm{yld}}(y)$ the binary number, harvest (1) or not (0) in year y (dimensionless-indicates whether biomass is harvested in a particular year).

Total production costs are calculated as follows. For each part of the production chains, the annual discounted investment and operational costs are calculated based on literature and expert knowledge. The total biofuel production costs (C_{biofuel} (\$/$\mathrm{GJ}_{\mathrm{biofuel}}$) are calculated following Eq. (3):

$$C_{\mathrm{biofuel}} = \frac{\sum_i(\alpha \times I_i + O\&M_i + F_{\mathrm{ci}} + T_{\mathrm{ci}})}{\mathrm{Biofuel\ production}} \tag{3}$$

where α is the annuity factor, I_i investment costs for supply chain stage i (\$), $O\&M_i$ – operation and maintenance costs for supply chain stage i (\$), F_{ci} – feedstock production costs (\$), T_{ci} – transportation costs for supply chain stage i (\$), Biofuel production (GJ/yr).

The annuity factor is calculated with Eq. (4):

$$\alpha = \frac{r}{1-(1+r)^{-\mathrm{equipment\ lifetime}}} \tag{4}$$

where r is the discount rate.

For second generation biofuels, the fuel conversion stages are especially capital intensive. It is also important to take note of the relevant equipment specific cost factors (lifetime, interest rate, etc.) and different cost type information (capital-related and installation, consumption-related and operation related). As second generation technologies are not yet mature, it is necessary to incorporate time dependent technological learning and scaling up effects in the economic analysis to make future projections.

2.3.1. Future changes in biofuel production costs – key assumptions

Bioenergy production costs are expected to change over time due to a number of factors. Hoogwijk et al. [35] provide a global long-term outlook for potential perennial biomass production costs under different IPCC scenarios. In the future, improved seeds and breeding as well as technological learning about seed technology are expected to result in higher biomass yields which will result in decreasing production costs. Key factors that affect the costs of bioenergy production include future biomass yields, land rent, labour costs, equipment costs, agrochemical inputs costs, oil prices, technological learning and development, growth in demand for bio-based industries, local and international policies.

Land rent: Long term pressure on land is expected under a business as usual scenario and thus the cost for land is likely to increase. The increase is mainly due to population growth, food demand and environmental degradation. Pressure on the available land can be offset by increases in yield.

Labour: As each country's economy grows, it is expected that labour wages will increase. For Mozambique, unskilled labour costs are expected to double from about \$2 to \$4 per day by 2030. Likewise semi-skilled labour is expected to increase from about \$4.2 to \$7.5 per day in 2030 [21,33].

Technological learning and improved crop productivity: Technological learning and adoption of more advanced management practices are important in future biomass energy feedstock cost reduction. In studies on the cost development of sugarcane in Brazil [36], corn in the US [37], and rapeseed in Germany [38], the experience curve approach was applied in which the development in costs are related to the cumulative production. These studies showed that an increase in productivity is the most important driver for decreasing production costs for feedstock, contributing 65–85% to the total cost decline. The remaining 15–35% cost reductions are attributed to increasing economic efficiency in production operations. However, these developments could be counteracted by future price increases of inputs such as diesel, fertilizers and chemicals [36].

Prices of various inputs: The most important inputs in energy crop production include fertiliser, chemicals, fuel, and machinery costs. Globally, fertiliser prices will increase due to higher fossil fuel prices. All these factors are quite uncertain and are expected to have varied impacts on the biomass production costs, but increase in yields is likely to have a much bigger impact on overall costs – and thus future costs are expected to decrease. The development in yield is selected as the most suitable parameter for the assessment of cost developments over time [39]. Estimates of the maximum attainable yield are based on current yield levels in each country extrapolated using historical and expected growth rates.

2.3.2. Future performance of conversion technologies

Although available knowledge is limited, estimation of the future cost development of biofuel conversion technology (especially second generation biofuels) can be estimated using the technological learning concept. Considering the timeframe up to 2030, it is most likely that the biofuel conversion production processes will improve and that more plants will have been built. Numerous studies [40–42] have shown that as cumulative installed capacity increases the costs for installing a specific capacity decrease. The rate at which costs decline for every doubling of cumulative capacity is expressed as the learning rate [43]. The extent to which technological learning has effects on the cost of production in 2030 depends on the assumed learning rate and the cumulative installed capacity which can be achieved in the period up to 2030. We consider specific cost reductions through upscaling (scale-dependent learning) as an integral part of overall cost reductions over time. The majority of other supply chain activities and technologies, such as biomass pre-processing, are assumed to be mature and unlikely to achieve significant learning in the next two decades. Applying this approach, we use the methodology as detailed in de Wit et al. [43] and Knoope et al. [42] into estimate future biofuel conversion costs. We also use the learning rates as given in [43].

2.4. Data

The calculations are based as much as possible on specific country data such as wage rates, input costs and yield. Information on yield is based on literature sources and expert knowledge and was supported and verified by country partners.[3] The amount of labour that is required per feedstock has been kept constant for the different geographical regions and is based on expert agronomic knowledge and selected literature that include sufficient detail (the soy calculations in Argentina e.g. are based on [44]). The local country partners also assisted in data collection. Very detailed data on palm production by smallholders in Sumatra Indonesia was obtained through another project – the Global Biopact project in which different smallholders were interviewed and many literature sources were combined [45]. The data has also partly been collected and verified by fieldwork in Mozambique (in 2010 and 2012), Tanzania (in 2006–2009, 2011) and Mali (in 2011).

The complete input data sets used in the calculations are provided in Appendices B and C.

3. Results

3.1. Economic performance of 1st generation biofuels

3.1.1. Soy

All 7 settings that concern soy are situated in Argentina, a country that has a lot of experience with soy cultivation. Over the last decades, soybean cultivation has grown substantially to a production of more than 53 million tons in 2010 [46]. The main product of the cultivation of soy is animal feed while the oil that is obtained from processing is considered a by-product. Therefore, the cost of feedstock production is only allocated to soy biodiesel by 20% (by mass), but we also included price allocation (36%) to show the difference. Soy cultivation in Argentina typically takes place on large scale plantations with high rates of mechanisation. The management systems that are varied are the rate of mechanisation and the practice of tillage. Furthermore smallholders and plantations are incorporated as well as two timeframes: 2010 and 2020.

Soy yields have increased on average with more than 50% since 1970, although there are large differences between the provinces [47].[4] Increased yields are explained by a conjunction of factors including: agronomic, genetic, farm machinery and general management. There are good perspectives for this tendency to continue in the near future. Soybean BTRR2 specifically developed for the southern hemisphere could generate an increase between 10% and 15% in yields [47]. We have increased the yields for 2020 but up to a maximum of 5 tons/ha, See Table B2 in the appendix for the yields used in the calculations, they are based on specific provinces in Argentina and are also discussed below.

Prices for inputs and soy beans change over time. The production costs of soy have increased since 2002, but dropped between 1991 and 2002, current costs are at a similar level as 1991, Therefore the same prices for inputs in 2010 and 2020 were used. Wages are expected to increase from 3.18 $/h in 2010 to 8.29 $/h in 2020.

Transport distances vary greatly, since Argentina is a large country. For setting 1 and 2 an average of 400 km between field and conversion plant is taken, based on the production regions described above [46]. The transport costs are 0.06 $/ton km [27]. The revenues are based on the market price for soy beans of 169 $/ton [47]. This price can vary; the lowest price is 152 and the average price between 2005 and 2010 is 327 $/ha. This last price is based on international prices and while Argentina has an export tax on soybeans, internal prices are 24% lower than international prices which leads to 246 $/ton which is used as upper range [46–48]. Prices have increased since 1980 so it is unlikely that the default value of 169 $/ha will decrease. See Table B2 in the Appendix with all other input data per setting.

Fig. 1 shows the breakdown of agricultural inputs and the calculated NPV of soy production in the selected settings. Setting 1, 2 and 5 are located South of Cordoba (rio Cuarto), setting 3 and 6 in Pergamino and Pehuaio (North and West of Buenos Aires) and setting 4 and 7 South of Sante Fe.

In setting 1 and 2 only the endproduct (SVO and biodiesel) is different, the feedstock production costs are therefore equal. A main difference between the settings, related to differences in management (tillage) and location, is the yield which is 2.8 t/ha/yr in setting 1 and 2, 3.6 ton/ha/yr in setting 3 and 4.5 ton/ha/yr in setting 4. In the 2020 settings the yield is 4 and 5 ton/ha/yr for setting 5 + 6 and 7 respectively. Setting 5 includes irrigation which is why costs are higher. The NPV is positive in all cases, quite low in setting 1–3 (around 200 $/ha) and setting 5 (around 300 $/ha) and high in setting 4 and 7 (2000/3000 $/ha over the 24 years). However, soy biodiesel is only a by-product and agricultural producers receive most benefits from selling soy meal. Furthermore, the default NPV value is quite low considering the upper range using a market value of 246 $/ton soybeans which leads to very high NPVs of 2500–7000 $/ha/lifetime, and the fact that market prices for soybeans have risen over the past decade [47]. On the other hand, large investments are required to purchase machinery for (no-tillage) cultivation, machinery costs are included, but the investment needs to be made upfront. Fig. 1 furthermore shows that land rent is a relatively important contributor (25–33%), but also herbicides (≈20%) and insecticides (≈13%) are significant cost factors. The value of land rent that is used in the calculations is 150 $/ha/yr. This value is quite low, compared to other sources that mention prices of 200 $/ha/yr (INTA 2011b) or even higher (commercial) rates of almost 520 $/ha/yr. This would reduce the NPV in all settings to negative values (−3700 to −900 $/ha). The highest

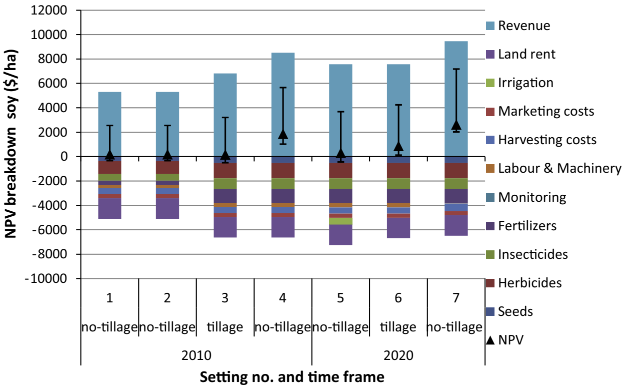

Fig. 1. Costs, revenues and NPV breakdown for soy production in setting 1–7 (all Argentina), setting 1 includes only SVO production, setting 1 and 2 have low mechanisation rates, setting 5 includes irrigation. NPV is calculated using a market price for soybeans of 169 $/ton with a range of 152–246 $/ton.

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[3] The local country partners are: Scientific Engineering Centre Biomass (SEC Biomass) in Ukraine, the national institute of agricultural technology (INTA) in Argentina and the agronomic research institute (IIAM) in Mozambique. Furthermore we collaborated with the company Cenipalma in Colombia and Prof. Gheewala from the university of Bangkok, Thailand.

[4] E.g. Cordoba reached an average yield gain of around 300% in the last 10 years whereas Corrientes and La Pampa reached an average yield gain of around 60% in the same period.

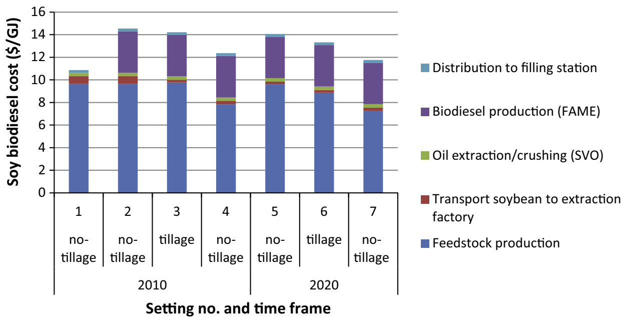

Fig. 2. Soy biodiesel production costs for setting 1–7, all in Argentina, setting 1 includes only SVO production, setting 1 and 2 have low mechanisation rates, setting 5 includes irrigation.

NPV is obtained in setting 7 (>2600 $/ha), a high yield in combination with no tillage which saves labour and machinery costs (but increases herbicides costs). In Fig. 2 the total production costs of soy biodiesel are provided.

The price per GJ for soy biodiesel in Argentina is relatively low, of the feedstock costs only 20% (by mass) is allocated to soy biodiesel since the main use is animal feed. If allocation is done by price (36% allocated to biodiesel) than total costs are between 12 and 15 $/GJ (214 $/ton for meal and 580 $/ton biodiesel [27,48]. The lowest costs are obtained in setting 4 and 7, both settings with no tillage. The feedstock costs contribute more than 45% to the total costs. Biodiesel processing is the second largest component that contributes more than 40% to overall costs. The distance from field to factory, which is relatively large in setting 1 and 2, has a limited effect on the overall price, partly because transport is efficient in Argentina.

3.1.2. Sugarcane

The settings that relate to sugarcane are located in Brazil and Mozambique. Both countries currently produce sugarcane and sugar, but only Brazil produces ethanol. In Brazil two production systems exist; large scale plantations and outgrowers who deliver to a central processing unit. The latter is used in our calculations. The production system is placed in North East Brazil (NE), a region which has higher production costs compared to the Central South region of Brazil (CS) (where sugarcane ethanol prices are globally the most competitive), but there is also quite a lot of room for improvement. Cultivation practices have not changed much in the last decade and are not optimal. Mechanised harvest is not practised at a very large scale in the NE, but policies in Brazil require a gradual implementation, which will potentially drive other improvements. Furthermore the NE has the advantage of having several large harbours that are relatively close to the production facilities.

Both production systems also exist in Mozambique. Outgrowers often obtain almost all inputs from the central processing mill, while their only input is labour. There is a large difference between very suitable soils and less suitable soils. Xhinavane is a production region close to Maputo that has been selected for irrigated production, while the Dombo region (more in the Central region) with more suitable soils is selected for non-irrigated production. Sugarcane is cultivated in 5-yrs ratoon cultivation, the crop is planted in year 0, harvested every subsequent year and is replanted in year 6.

Two settings (10 and 15) consider both 1st and 2nd generation ethanol, ethanol produced from the juice (1st generation) and from the bagasse (2nd generation). Every ton of bagasse produces 88.3 l ethanol [49].

The yield for the NE is based on [6] and is 60 ton cane/ha/yr for non-irrigated cane and 90 ton ha/yr for irrigated cane. The yields in Mozambique (76 t/ha/yr non-irrigated and 100 t/ha/yr irrigated) are based on [50,51]. The higher yields in Mozambique are explained by the high climate suitability of Mozambique for sugarcane. Per ratoon year the yield is expected to decrease to respectively 96%, 92%, 88%, 83% and 79% of the maximum yield. Yields are projected to increase with 5% in 2020 compared to 2010.

Transport costs in Mozambique are quite high; 0.096 $/ton km, for Beira region, while for Brazil they are 0.06 $/ton km [52]. Land rent in Mozambique is assumed to be 22 $/ha/yr. Depending on the type of land (bare land, agricultural, etc.) this price can vary, for example agricultural land that is leased from the Government has only a tax fee of around 0.5 $/ha/yr (MZM 15/ha/yr) [53]. See Table B3 in the Appendix with all input data.

The market value for sugarcane that is included as default value is 35 $/ton, based on the actual price paid in a sugarmill in Mozambique [54]. Cane prices fluctuate, an important aspect is the quality of the cane (the sugar content). In 2005–2010 sugarcane prices ranged from 24 to 38 $/ton in South Africa (a market very close to Mozambique), but from 15 $/ton in Mozambique which is used to show the range in NPV [55]. See Fig. 3 for the results of the NPV calculations for sugarcane production in Mozambique (setting 11–17).

All NPVs in the settings for sugarcane production in Mozambique are positive, varying from 2700 to 5000 $/ha. Note that in setting 12 and 17, it is assumed that the instalment costs for irrigation are accounted for by the central producer; the outgrower has to account for the labour that is associated with irrigation. Because of the higher yield in these settings the revenue is also higher which leads to a higher NPV. The NPV is negative for the settings if the low market value of 24 $/ton is used. Although the price paid in 2010 was 35$, the market prices for sugarcane fluctuate with the global sugar prices and therefore are very volatile. Furthermore, The Mozambican farmers association is weak which leads to low prices [56]. The analysis shows that the NPV is very sensitive towards price changes on the other hand producers can choose the highest price (sugar or ethanol). Harvest and delivery accounts for the largest costs (33–42%), also fertilisers, labour and mechanic equipment such as tractors and ripeners are large cost factors (8–13%). For setting 8–10 and 13–15 (Brazil) the agricultural breakdown is based on detailed calculations by [6].

In Fig. 4 the total production costs are provided for all settings that relate to sugarcane (8–17).

Sugarcane ethanol (incl. 2nd generation next ethanol) can be produced for 21–26 $/GJ in 2010 and 20–23 $/GJ in 2020 in our

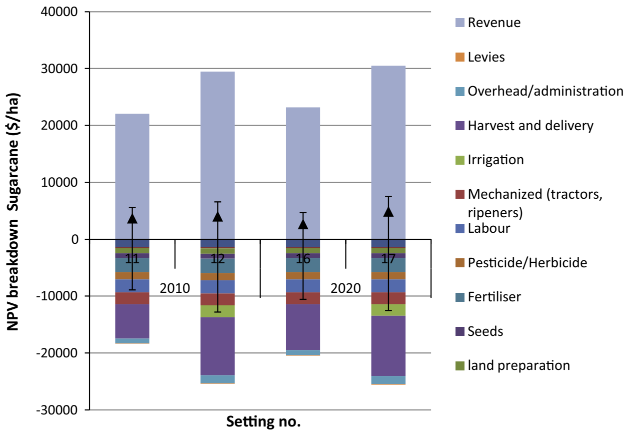

Fig. 3. Costs, revenues and NPV per ha for sugarcane in Mozambique, settings 11 (no irrigation), 12 (irrigation), 16 (no irrigation), 17 (irrigation). Market price range used for NPV 15–38 $/ton cane, default value is 35 $/ton.

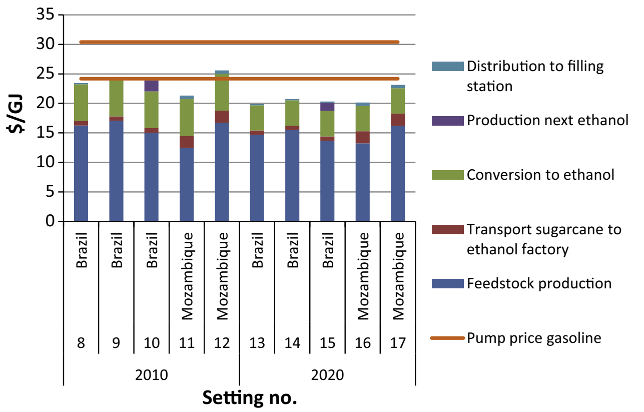

Fig. 4. Sugarcane ethanol production costs per GJ in selected settings (8–17) (max pump price of gasoline is in Sao Paulo based on [36], min pump price is the price of petrol in Mozambique in 2009 excluding taxes, ethanol energy content 26.4 MJ/l), settings that include irrigation are: 9, 10, 12, 14, 15, 17 the other settings do not include irrigation.

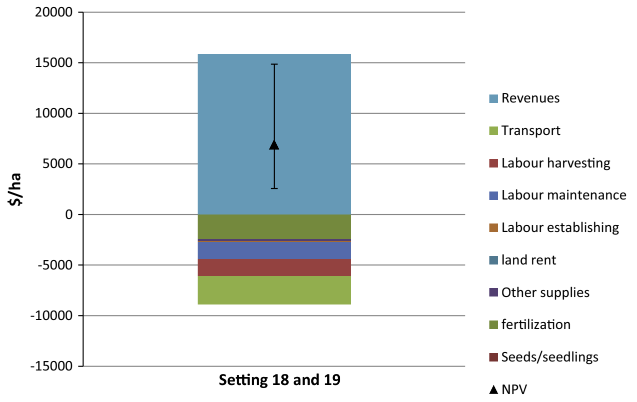

Fig. 5. Costs, revenues and NPV breakdown (over 24 years) for palm oil in Indonesia, setting 18 (smallholders, SVO) and 19 (smallholders, FAME), NPV is calculated using default market price for FFB of 120 and a range of 87–180 $/ton.

study. The total production costs of sugarcane ethanol are close to being competitive to its fossil alternative. This is especially the case in 2020 (settings 13–17, 20–23 $/GJ), where conversion costs are expected to be lower and yields increase. In the IPCC cost estimate for sugarcane ethanol from Brazil the sale of electricity has been included which leads to an even lower estimate of 15 $/GJ. The difference in production costs between Brazil and Mozambique are marginal, this is partly due to the high suitability of Mozambique for sugarcane and hence high yields. The transport expenses on the other hand are higher in Mozambique than in Brazil, in Brazil the sugarcane plantation in the North East are quite well connected to the harbour.

3.1.3. Palm

The palm oil settings that are selected, refer to production in Colombia, Indonesia and Malaysia. Malaysia is the largest exporter of palm oil and is considered to operate on a best-practice base. Colombia currently has >400,000 ha of oil palm plantations and is the worlds' fifth producer [57]. For this cost calculation section we have added a setting for palm oil production 2020 in Colombia, setting 21b.

For Indonesia the setting is located in Jambi (Harapan Makmur village) on Sumatra. Outgrowers are mainly small-scale farmers, who on average own a 2 ha farm. They obtain a relatively low yield, which appears to result from a range of factors related to sub-optimal management practices. Farmers farm their own land using family labour. Fertiliser application, the largest cost component of farmers' operating costs, is variable. Farmers currently apply a mix of inorganic fertilizers [45].

In Colombia production systems are present with small, medium and large scale oil palm growers. Especially for outgrowers, improvements in yield and the amount of hectares planted are expected to increase in the future. Cost data is derived from CENIPALMA (Investigación e Innovación Tecnológica en Palma de Aceite) and [32]. Data from Malaysia is obtained from [58]. For Colombia and Malaysia only discounted total input data was available, therefore no NPV analysis is included. All input data can be found in Table B4 in the Appendix.

In Fig. 5 the NPV is shown for palm production by smallholders in Indonesia (setting 18). Yield is expressed in Fresh Fruit Bunches (FFBs), it is estimated that Indonesia (16 ton FFB/ha/yr) reaches the yield level of Malaysia (19 ton FFB/ha/yr) by 2020. This is relatively conservative since a case study plantation in Malaysia, analysed by Wicke et al. [59], yielded 25 ton FFB/ha/yr. Better genetic varieties can increase yields. Also for Colombia the expectation is that yield levels will reach Malaysia. Although Bud rot disease can seriously affect yields and has done so in Colombia, hybrid materials have been developed but it takes some time before they are in production [57]. The benefits are based on the market value for FFB of 120 $/ton, which is based on the lower price of FFBs for smallholders in North Sumatra (between 0.12 and 0.18 $/kg). Wages are 3 $/day and farmers have to pay for transport of their FBB at a rate of around 2.2 $/kg/km [45]. The price determination varies every month and is also based on the oil content in the FFBs [60]. The marketprice is varied from 87 to 180 $/ton to show the sensitivity of FFB production [45,60].

The major cost item for total inputs in the settings for smallholders is labour (39%) followed by fertiliser (27%). Especially labour that is required for harvesting is a large cost factor. The NPV for Indonesian farmers is high (6900 $/ha). This is due to relatively low costs for land rent (annual land tax) in Sumatra (2 $/ha/yr), the short distance between farmers and processing factory (7 km), and the long yearly returns of palm. Nevertheless the cashflow is only positive from around year 4 onwards, which means farmers have to be able to make such investment up front. Smallholders also have to pay for transport expenses to the mill which is included in the calculations. Fresh Fruit Bunch (FFB) prices are volatile and since they have to be processed within a short time frame (2 days), farmers often do not have a choice but to sell them for a (set) price to the mill. The NPV using the lower market price of 87 $/ton is 2500 $/ha/lifetime which is still profitable. The agricultural breakdown for setting 21 (Colombia) is based on [32], and for Malaysia based on [58,61], more data is needed to calculate specific NPVs. Fig. 6 shows the total feedstock production costs and transport and processing costs for all settings related to palm oil (18–24).

Palm oil can be produced between 12 and 22 $/GJ in 2010 and between 8.5 and 12 $/GJ in 2020 in our study. Palm biodiesel can be produced at very low costs in Malaysia (≈13 $/GJ), which is lower than the IPCC estimate of 26 $/GJ but falls within the range they provide of 10–12 $/GJ based on [63] in [8]. Currently the cost of producing palm biodiesel is relatively high in Colombia (22 $/GJ), but it is expected that Colombia can produce for similar low costs as Malaysia, if yields can be increased. This situation is included in setting 21b in Fig. 6. Production on a plantation (setting 20) is possible at lower costs than production with smallholders (setting 18 and 19). In 2020 (setting 23, 24), palm biodiesel can be produced at very competitive prices due to lower refining and esterification costs (9–12 $/GJ).

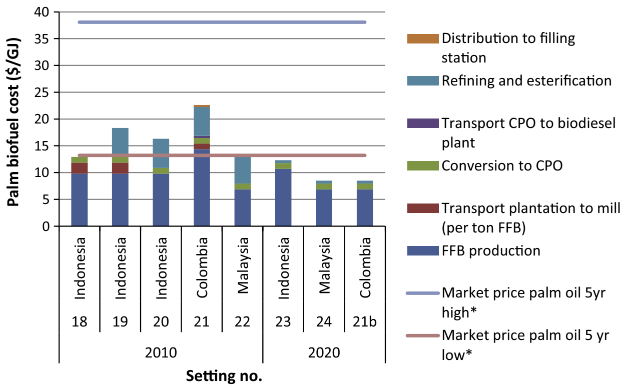

Fig. 6. Cost of palm oil production (Crude Palm Oil (CPO) and biodiesel) in Indonesia, Colombia and Malaysia; energy content 36.92 MJ/l [62], Setting 18, 19, 21, 21b are based on smallholders, the remaining settings on plantations, setting 18, 19 have low inputs, setting 21, 21b intermediate inputs and setting 20, 22, 23, 24 have high inputs. *: Source for market price palm oil: [48], based on 2008–2013, the highest price was 38 US$/GJ (1250 $/ton) (February 2011) and the lowest 13 $/GJ (433 $/ton) (November 2008).

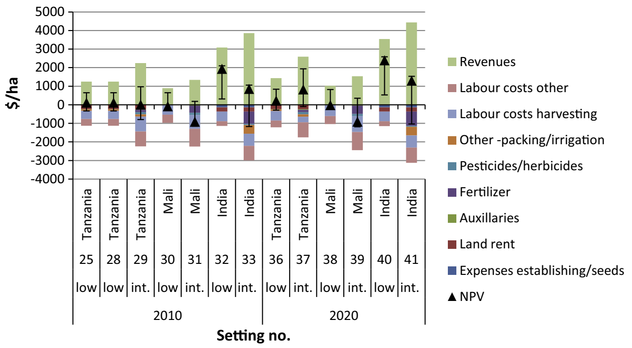

Fig. 7. Costs, revenues and NPV for jatropha settings 25–41 (excluding plantation settings 26, 27, 34 and 35) over a lifetime of 24 years, all smallholders, low = low inputs, int. = intermediate inputs, the difference between setting 25 (SVO) and 28 (FAME) is the fuel output, the NPV error bars show the response of the NPV to a market price variation of jatropha seeds of 0.09–0.20 $/kg.

3.1.4. Jatropha

Three countries are included: Tanzania, Mali and India as well as three different management settings: low inputs, intermediate inputs and high inputs. A production system with smallholders and a plantation is also considered. The difference between smallholders and plantation farming is explained in [64]. Jatropha seeds are harvested from year 2–24, harvest periods in Tanzania are end of November (depending on the rainy period) and July–August. In India the harvest period is July–August and October–November in Karnataka [65]. All three countries produce jatropha, however commercial experiences are limited. The amount of oil produced is relatively low, so therefore most cost data is derived from a small-medium sized extraction plant. Large investments have been made in Jatropha research so efficiency improvements are expected. On the other hand some large scale operations halted their activities because of disappointing results and the lack of financial resources [66].

The cost factors are different for smallholders and a plantation system. A difference between the countries is that for Tanzania it is assumed that farmers have to pay for packaging, 0.45$ per bag of 60 kg, these expenses are not accounted for in Mali and India. Bags are also often re-used.

The plantation setting is situated in Tanzania, the low input setting (no 27) represents a plantation based with manual labour, while the intermediate input setting (26) represents mechanised harvesting, see [64]. In the 2020 settings, the parameters for the mechanised harvester are changed, the price is decreased by 60% (from 180,000$ per harvester to 60,000$) and the harvesting speed is increased from 1.5 ha/h to 3 ha/h. For both production systems the costs are linked to the yield. Wage rates are relatively low in the countries, and only low skilled labour is required for cultivation. For all three regions the labour requirements have been kept constant, total labour requirements for jatropha depend on harvest and vary between 30 and 120 days/ha/year.

Jatropha is a perennial crop with a productive lifetime of >30 years. For this study, an economic lifetime of 24 years has been used. The plant matures in 6 years' time; the first year 0% of the mature yield is expected. In the second year 10% of the yield is expected and 25%, 40% and 80% in the subsequent years until year 6. Furthermore, for 2020 the yields are expected to increase by 15% considering large efforts in Jatropha breeding programs [67].

The price for jatropha seeds that is paid to farmers is based on actual prices paid in the countries; 0.14 $/kg in Tanzania, 0.11 in Mali and 0.19 in India [21,65,68]. Van Eijck et al. [21] have made an extensive analysis of market prices for jatropha seeds (no other commercial markets for the seeds other than a very small share for the soap market exist). In the NPV calculations a range of 0.09–0.20 $/kg for all countries is used to show the sensitivity.

Since Jatropha production has not reached commercial levels, costs of conversion to SVO and biodiesel are relatively high; 0.20 $/l and 0.28 $/l respectively [21]. In India there is a well-established oilseed sector, therefore the conversion costs to SVO are lower (0.14 $/l [65]. Conversion and transesterification costs for 2020 (0.02 $/l) are based on US biodiesel conversion plants that are also used by [20]. All input data can be found in Table B6 in the Appendix. The calculated NPVs for jatropha production in setting 25–41 is shown in Fig. 7.

For quite a number of settings the NPV is negative. The profitability for farmers mainly depends on the yield that can be obtained and prices that are paid for the seeds [21]. Only with relatively low labour costs (or family labour when there are limited other options) and an average yield (2.3 ton/ha/yr) the NPV can reach values above 2000 $/ha (India, setting 40). The upper range of the market price, 0.20 $/kg would make jatropha production profitable in all settings, but the lower range, 0.09 $/kg would lead to unprofitable production (taking a wage rate of 2 $/day into account). In our calculations, there is no value for the by-product jatropha seedcake assumed for smallholder producers. However, if a jatropha processor can sell this seedcake (as briquettes or charcoal), the price paid for seeds could increase to 0.20 $/kg, it already reached almost 0.19 $/kg in Tanzania at this moment (personal communication, EcoCarbone 2013).

The two plantation settings are different in their production system and cost structure, in setting 26 (mechanized labour) production costs per kg are 0.24 $/kg seeds, while in setting 27 (manual labour) these costs are 0.26 $/kg seeds. The difference is due to the relatively high price of the harvester, which is expected to decrease in the future (for more details see [64].

The cultivation of Jatropha is very labour intensive. That is why wage rates have a large influence on feedstock production costs. The wage rate of India is relatively low (1.29 $/day[5]), compared to Tanzania (2 $/day [21]). The wage rate of Mali is (slightly) higher with 2.47 $/day [70]. Intermediate inputs in India also includes irrigation which is why these settings (33 and 41) have higher costs than cultivation without irrigation (32 and 40).

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[5] This is the minimum agricultural wage (Rs 60/day) (Altenburg et al., 2009) [69] Altenburg T, Dietz H, Hahl M, Nikolidakis N, Rosendahl C, Seelige K. Biodiesel in India, Value chain organisation and policy options for rural development. Studies 43. Bonn: German Development Institute (Deutsches Institut für Entwicklungspolitik); 2009.

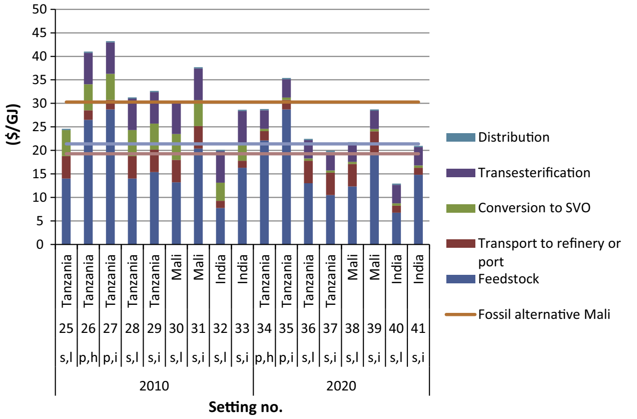

Fig. 8. Costs per GJ for jatropha SVO and biodiesel for setting 25–41, compared to the price per GJ of the locally available fossil diesel (fossil alternative Tanzania is based on diesel price minus government taxes and dealers profit, see [21], fossil alternative Mali and India represent the retail price of diesel in Mali and India respectively, based on [71]) s = smallholders, p = plantation, l = low inputs, i = intermediate inputs, h = high inputs.

Fig. 8 shows the total production costs of jatropha SVO and biodiesel in Tanzania, Mali and India.

Jatropha can be produced for 20–42 $/GJ in 2010 and 13–25 $/GJ in 2020. Transport expenses are quite low in India compared to the African countries. If infrastructure improves these costs can be lowered but this has not been taken into account in the analysis.

In almost all settings, jatropha biodiesel is currently not competitive with fossil fuel. If wages are very low (eg. In India) or if yields are increased (settings 34–41) in 2020, jatropha based biofuel production becomes more promising but there is still a large variability (and thus uncertainty) of 13–35 $/GJ.

The wage rate has a large influence on the costs, due to the high labour requirements for harvesting. Yields are currently quite low, since this is a relatively new commercial crop, but there is room for improvement. The NPV is high when low amounts of inputs are used, whereas high amounts of expensive fertilizer decreases profitability up to a point where farmers can make a loss. With low wage rates (e.g. family labour) profitability is reasonable, but conversion and transesterification costs have to be reduced to rates similar to US conversion plants (0.02 $/l), used in the 2020 settings, which is likely if more commercial experience is gained with processing jatropha oil, to make the end product competitive with fossil diesel.

3.1.5. Cassava

Cassava is currently cultivated in large parts of the world, often by subsistence farmers as source for food. Cassava roots can be stored in the soil for two years, serving as food storage [72]. Small scale farmers cultivate cassava as an additional crop on their land, and in between other crops. These cultivation management techniques are often far from best practice. In Thailand, more commercial farming of cassava exists and the first (pilot) cassava to ethanol conversion plants have already been established. In Mozambique the first ethanol plant has been established as well (in Sofala province, capacity of 2 M l/year) but in Tanzania such facilities do not exist yet. Data on cassava cultivation is obtained from [21], IIAM Mozambique, [73,74] and through personal communication with Prof. Gheewala (The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, Thailand), Thea Shayo in Tanzania [75], Sicco Colijn and Boris Atanassov in Mozambique (2010, 2012).

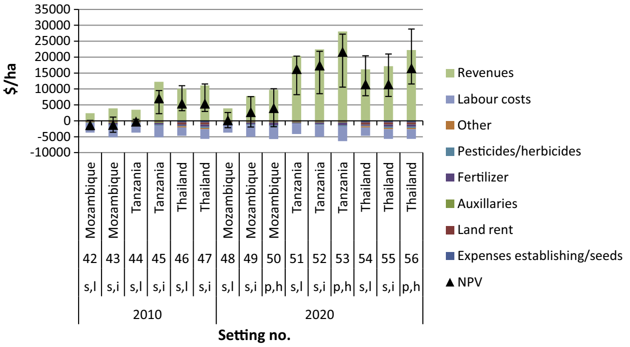

Fig. 9. Costs, revenues and NPV for cassava in settings 42–56, ($/ha), s = smallholder, p = plantation, l = low inputs, i = intermediate inputs, h = high inputs, lifetime is 24 years, the NPV upper and lower limit is calculated using market value ranges for fresh roots in Mozambique 23–94 $/ton, Tanzania 55–109 $/ton and Thailand 35–70 $/ton.

The NPV for producing cassava feedstock in the different settings (42–56) is shown in Fig. 9. The current market price for fresh cassava roots is based on the food market price, since there are hardly ethanol producing facilities yet. Revenues are based on farm gate prices for fresh cassava roots, which is 58 $/ton in Mozambique, 91 $/ton in Tanzania and 45 $/ton in Thailand (the average during 2006–2008). Prices for fresh roots fluctuate due to seasonal influences and supply and demand. In Thailand the price ranges between 35 and 70 $/ton$_{\text{fresh}}$ during the same time frame. In Mozambique prices range between 23 and 94 $/ton$_{\text{fresh}}$[6] and in Tanzania 55–109 $/ton$_{\text{fresh}}$ which is included in the NPV sensitivity analysis [21,76]. Differences between the countries are especially due to high transport expenses for buyers in Tanzania and Mozambique. Sometimes the farmers have to account for the transport expenses themselves. The amount of labour days for Thailand is much lower (around 44 days/ha/yr [73]) but the use of agricultural equipment is higher. The labour costs for Thailand are based on averages from 2005 to 2008 [77]. There are no costs for fertiliser included in the low input settings for Mozambique and Tanzania. This is done because the fertiliser applied is expected to be derived from manure that is freely available. The input costs for Thailand are averages from 2005 to 2008 [77]. The amount of labour required for cultivation in Mali and Tanzania are expected to reduce in 2020 to only half of the amount of 2010. This is due to increased mechanisation that enables labour rates more equal to Thailand. The labour requirements for Mozambique and Tanzania are based on [21]. 142 labour days per year are required for the low input system and 165 days/ha/yr for the intermediate input systems. The difference is due to the labour days required for additional management such as fertiliser, pesticide and herbicide application and pruning. Since there are currently no large scale plantations for cassava cultivation, these are only included for 2020, when it is expected that commercial plantations could start up.

Cassava is harvested every year, but a fair comparison with other systems in this study, a lifetime of 24 years is used. In the low input system in Mozambique and Tanzania it is assumed that due to poor fertiliser application, the yields decline by 2% per year. In Thailand, current practice is to apply fertiliser, therefore yields are assumed to be stable over the years. For the settings that relate to 2020, it is assumed that Mozambique reaches yield levels of Tanzania, and Tanzania reaches yield levels of Thailand without declining yields over the years, see Tables B7 and 8 in the Appendix for more details.

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[6] Prices for dried cassava are around 150 $/ton delivered tot he factory gate of a cassava ethanol plant in Mozambique (Personal communication, manager Cleanstar).

Except for the 2010 settings (42, 43 and 44) with low yields, all NPVs are positive ranging from 180 to 16,500 $/ha/lifetime. In 2010, settings 45, 46 and 47, are still profitable (Tanzania and Thailand) with NPVs of 2200–5000 $/ha. This is due to the higher yields that make up for additional expenses on fertiliser and other inputs. Fresh cassava roots need to be marketed relatively fast, unless they are dried. All settings that relate to 2020 (setting 48–56) have positive NPVs (from 180 to 16,000 $/ha) and excluding the low input setting in Mozambique (setting 48), the range is higher with 2800–16,000 $/ha). The NPV is quite sensitive towards changes in market prices, especially in Mozambique, all settings have negative NPV values when the lower market price is used. In the other countries even low prices result in a positive NPV. Labour costs are the major cost contributor, while for Thailand land rent is also a relatively large contributor. The yield and cassava price have a large effect on the profitability.

Fig. 10 shows the costs of cassava ethanol production for the different settings in Tanzania, Mozambique and Thailand. Cassava ethanol can be produced in our study between 22 and 46 $/GJ in 2010 and between 15 and 21 $/GJ in 2020. In 2010 prices, none of the settings can obtain cassava ethanol for costs below current fossil petrol prices. However, with anticipated increase in yields (in Mozambique from 4–6 to 6–15 tons/ha, in Tanzania from 6–12 to 20–27.5 tons/ha and in Thailand from 20–22 to 32–44, while even yields above 55 ton/ha are possible according to [78] and a reduction of conversion costs from 0.23 $/l to costs equal to corn ethanol conversion costs (0.14 $/l [37] which implies large scale factories and is based on US conditions), all 2020 settings could be competitive to current fossil petrol prices, except in Mozambique where yields are very low. The price of 0.23 $/l is derived from a pilot factory in Thailand where efficiency improvements and cost reductions are likely. Total costs for cassava ethanol in Tanzania and Thailand are between 15 and 21 $/GJ, which is lower than the estimate of IPCC (26 $/GJ in Thailand) [8].

3.2. Production costs of second generation biofuels

Second generation biofuel feedstocks largely consist of cellulose, hemicellulose and lignin [8,79]. Conversion to bioethanol fuel (EtOH) is via hydrolysis of the cellulose and hemicellulose to sugar, after which fermentation of sugar is performed. These feedstocks can also be converted to fuel via gasification or pyrolysis to produce synthetic diesel, bio-oil and other fuels [23,80].

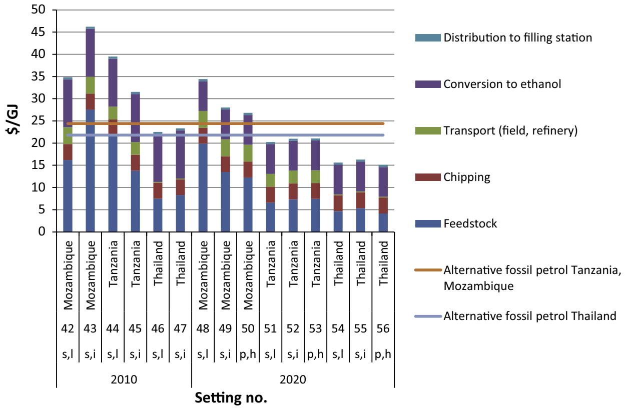

Fig. 10. Total production cost calculations for cassava ethanol (20.88 MJ/L), s = smallholder, p = plantation, l = low inputs, i = intermediate inputs, h = high inputs. Alternative fossil petrol price Tanzania and Mozambique based on [21], in Thailand based on data provided by prof. Gheewala. See Table A1 in Appendix A for setting specifications.

Generally, the advantage of next generation biofuels (over 1st generation biofuels) is their ability to utilise many different types of lignocellulosic materials as feedstock and lower land use impacts [8,81,82]. However, the environmental impact of lignocellulosic biofuels depends on the conversion route, the feedstock and site-specific conditions. Moreover, unlike the mature 1st generation biofuels, 2nd generation biofuel technologies are still under development (pilot and demonstration stages), and commercialisation is anticipated in the next decade [83].

We present below the estimated costs for producing 2nd generation biofuels from eucalyptus, switchgrass, poplar, wheat straw and rice straw. Similar to first generation biofuels, at each stage in the production of biomass, cost factors such as labour, machinery investment, fuel costs as well as chemical and energy inputs have to be accounted for. The technical specification of equipment such as tractors is also incorporated into the calculations. An important aspect in energy plantations, especially short rotation woody crops such as eucalyptus, is the ability to coppice over successive rotations periods until it is finally stumped out and replanted.

It is assumed that all feedstock production systems are carried out under well managed agricultural systems – meaning the proper application of appropriate amounts of fertiliser (to replenish plant nutrient extraction and support high biomass growth), pesticide and herbicides (to ensure protection of energy crops against diseases, pests and weeds). It also assumes adequate silvicultural management, but does not take into account irrigation. Planting is assumed to be done during the rainy season to take advantage of rain-fed growth. However, some water may be applied to young seedlings, during the first three weeks of growth, should they encounter moisture stress. More details on the feedstock production and information on conversion technology economics can be found in Appendix C and Batidzirai [23,83].

3.2.1. Second generation ethanol production costs from eucalyptus

Eucalyptus is considered as the energy crop for Mozambique and Brazil. In Mozambique, it is assumed that seedlings are planted manually at a spacing of 3 × 3-m in a semi-arid region. Extensive manual weeding and chemical pesticide application are required during the first 3 years, before the eucalyptus trees reach full canopy cover. Harvesting is carried out every 8 years over 24 years before the stand is re-established. It is assumed that in Mozambique, harvesting is done using chainsaws. Forwarding to the roadside is done using a skidder. Table C9 in Appendix C gives details of cost elements included in eucalyptus production in Mozambique.

Eucalyptus productivity in Mozambique is estimated to vary from 4.5 to 35 t_{dm}/ha [21,26,84–86]. For a given species, the biomass yield is a function of the management applied as well as climate and soil conditions. According to Van der Hilst and Faaij [51], the mean annual increase (MAI) is estimated to be 1.5% per annum. The projected maximum attainable yield in 2030 is still well below the estimated maximum attainable yield for Mozambique.

Similarly, for Brazil, eucalyptus production costs are estimated using a set of assumptions shown in Table C11 in Appendix C. Land rent differ depending on soil quality and range from 49 to 146 $/ha. Harvesting is assumed to be mechanised using Claas harvesters. Current Brazilian average yields of eucalyptus are around 42 m^3 ha^{-1} yr^{-1} (∼15 odt ha^{-1} yr^{-1}), from very marginal soils to the very suitable soils [87].[7] Projections for the Brazilian potential average vary, but are generally estimated to be around 50 m^3 ha^{-1} yr^{-1} (∼18 odt ha^{-1} yr^{-1}) [88–90].

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[7] The productivity of eucalyptus in Brazil is estimated to be 35–55 m^3 ha^{-1} yr^{-1} (Machado et al. 2013) [87]. Smeets and Faaij [34] give a range of 10–29 odt ha^{-1} yr^{-1}, the higher end representing very suitable soil quality.

Table 4
Eucalyptus production performance in Brazil and Mozambique on different land quality.

	Region	2020		2030	
Land quality →		Suitable	Less suitable	Suitable	Less suitable
Yield (t_{dm} ha^{-1} yr^{-1})	Brazil[a]	22	10	24	12
	Mozambique[b]	–	7	–	10
Production costs (USD/t_{dm})	Brazil[a]	2.4	3.3	2.2	2.9
	Mozambique[b]	–	3.9	–	3.3

Source:
[a] [91].
[b] [51].

Table 5
Summary of biofuel conversion technology costs. *Source:* [8,43,92,93].

Conversion factor	Next EtOH [a]		Fischer Tropsch CFB [b]	
	2020	2030	2020	2030
Base scale ($MW_{th\ LHV\ out}$)	160–400	160–400	180–400	180–400
Base investment ($/$MW_{th\ LHV\ out}$)	935–2020	840–1820	1140–3310	1130–2990
Scale factor	0.7	0.7	0.78	0.78
Lifetime	25	25	25	25
Load factor	90%	90%	90%	90%
O&M (% of investment)	4%	4%	4%	4%
Efficiency fuel only (LHVwet)	40%	40%	45%	45%

[a] According to Carriquiry et al. [94], capital investment costs for a 220 million litres per year cellulosic ethanol plant using 700,000 tonnes wood or switchgrass as feedstock are between 264 and 352 M$. They estimate the capital investments to be in the range of 1.06–1.48 $/l ethanol annual capacity while operational costs are between 0.35 and 0.45 $/l depending on feedstocks and technology. Future capital investments are expected to reduce to 0.95–1.27 $/l ethanol annual capacity and operating costs to 0.11–0.25 $/l ethanol. NRC [95] gives capital costs for a 40-million-gallon bioethanol facility as 174–223 M$ using poplar woodchips as feedstock. Corresponding costs with miscanthus, switchgrass, corn stover and wheat straw as feedstock are given as 176, 156, 150 and 123 M$. For different production capacities of 20, 40, 60, 80 and 100 million gallons per annum, the investment cost are respectively 117, 194, 264, 329 and 349 M$. Zinoviev et al. [79] estimate the investment costs for next generation bioethanol plant capacities of 15–185 $MW_{biofuel}$ to be 30 to 325 M€ to give specific TCI of 1800–2000 €/$kW_{biofuel}$. Chum et al. [8] compare costs of advanced bioethanol production technologies from various studies and give capital costs of 0.9–1.3 $/l ethanol annual capacity for plants in the range 150–380 million litres/yr. They estimate a 25% and 40%reduction in operating costs by 2025 and 2035 respectively.

[b] Batidzirai et al. [83] give the investment cost of BtL based on integrated gasification–Fischer Tropsch (IG–FT) technology using direct pressurised oxygen blown gasification (169 MW: 15MWe + 154 MW_{fuel}) at 332 M$. Zinoviev et al. [79] estimate the investment costs for FT fuel plant capacities of 130–220 $MW_{biofuel}$ to be 430–1000 M€ to give specific TCI of 2300–3480 €/$kW_{biofuel}$. According to Vogel et al. [92], BtL investment costs for the CFB technology are 543 M$ for a 500 MWth in scale (excluding 122.5 M$ pretreatment costs). NRC [95] estimates the cost of FT production based on a facility of 1.1 million t_{dm} switchgrass feedstock (3940 tons/day) to be 636 M$. The facility is designed for producing 4410 bbl/d and 35 MWe. Chum et al. [8] also give FT production costs of 17 $/GJ biofuel for 80 million litre annual production capacity, 8 $/GJ biofuel for a 280 million litre facility.

Eucalyptus feedstock production costs are calculated to be 3.9 $/GJ in 2020 and 3.3 $/GJ in 2030 in Mozambique and at the farm gate. For Brazil, production costs are 2.4–3.3 $/GJ in 2020 and 2.2–2.9 $/GJ in 2030 depending on land quality, see Table 4. These costs are dominated by fertiliser and harvesting costs.

The EtOH conversion technology route considered here involves use of physical and acid pretreatment followed by enzymatic saccharification of the remaining cellulose after which the resulting sugars undergo enzymatic fermentation to produce ethanol. A base capacity of 400 MW_{th} input capacity is assumed at a load factor of 90% (see Table 5). Investment costs are expected to decline from 374 M$ in 2020 to 290 M$ in 2030 due to learning effects in conversion technology.

For BtL conversion, the technology route considered is a combination of circulating fluidised bed gasification and turbular fixed bed FT reactor. A base scale of 400 MWth in is also assumed at a 90% load factor. Investment costs are expected to decline from 422 M$ in 2020 to 327 M$ in 2030 due to learning effects in conversion technology.

Fig. 11 provides a comparison of next EtOH production costs from eucalyptus in Brazil and Mozambique. At current conditions, EtOH could be produced at 19.8 $/GJ (in the range 14.5–30.3 $/GJ) in Mozambique and between 16.8 $/GJ (14–30 $/GJ) and 19.4 $/GJ (14.1–30 $/GJ) in Brazil. Corresponding long term costs are 18.5 (12.3–24.6) $/GJ, 16.9 (12.3–24.6) $/GJ and 16.2 (11.7–24.3) $/GJ. The range of values given in brackets represents the uncertainty in investment costs as found in literature.

Conversion costs dominate overall costs, accounting for around half of the production costs. The higher biomass feedstock production costs on marginal land explain the high fuel costs in setting 57

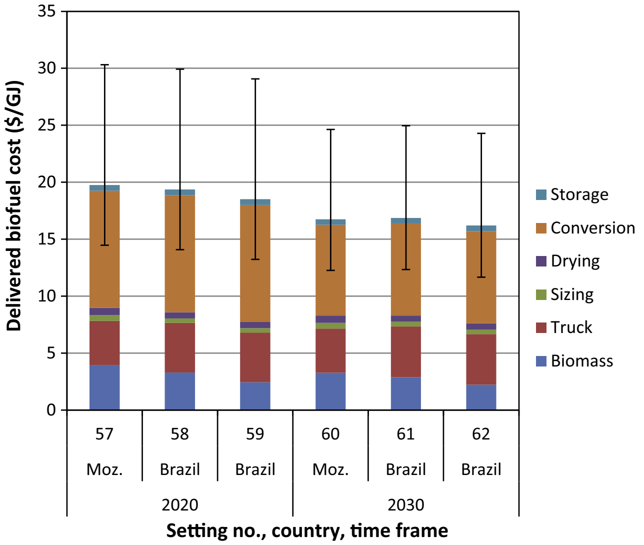

Fig. 11. Eucalyptus to next EtOH production costs (Moz = Mozambique and Brazil), the two settings in Brazil represent less suitable land (58, 61) and suitable land (59, 62).

and setting 58 (Brazil less suitable land). EtOH is produced at marginally higher costs in Mozambique mainly due to lower biomass productivity and higher feedstock production costs. Truck transportation is also a significant factor in overall costs contributing up to 27% of total fuel production costs.

3.2.2. Poplar (BtL production costs in Ukraine)

Currently there is no poplar production in Ukraine except for a few test plantations. Studies indicate that the optimal planting density of seedlings in Ukraine would be 4000–6000 plants/ha [96]. We assume a planting density of 5300 with 2 year rotation over 10 years. Poplar productivity is estimated to be 6 and 14 t_{dm} ha^{-1} yr^{-1} in marginal areas and suitable soils respectively. Table C10 (in Appendix B2) shows the amounts of fertiliser input requirements by land suitability. Wages vary from 0.63 to 2.1 $/h, while land rent is about 38 $/ha. Fuel costs range from 960 $/ton for diesel to 1080 $/ton for petrol. The current interest rate in Ukraine is 17% [97].

Poplar production costs are calculated to be 3.5 $/GJ on marginal soils in the short term, decreasing to about 3 $/GJ in 2030. Similarly, on good quality land, poplar can be produced at a cost of 2.3 $/GJ in 2020 and at 2 $/GJ in 2030. As shown in Fig. 12, harvesting represents the largest cost component for both marginal (35–38%) and good soils (29–31%), with the latter representing the long term. Fertilisation is also an important cost component contributing up to 29% of poplar production cost.

We assume poplar is used as feedstock to produce biodiesel in a BtL plant. The BtL conversion technology route considered is a combination of circulating fluidised bed gasification and turbular fixed bed FT reactor. A base scale of 400 MWth in is also assumed at a 90% load factor. Investment costs are expected to decline from 422 M$ in 2020 to 327 M$ in 2030 due to learning effects and increased efficiency in conversion technology (see Table 5).

BtL production costs in Ukraine are estimated to be 13.9–17.8 $/GJ for the selected settings under the base case, with the latter representing production on more marginal land in the short term. If variations in investment costs are taken into account the BtL production costs are calculated to be 11–42 $/GJ as shown by the error bars in Fig. 13. There is a 16% difference in costs between the short term and long term, mainly attributed to learning effects in agricultural production and conversion technology. See Fig. 13. Feedstock production costs and conversion costs dominate total costs, at 14–20% and 57–65% respectively. Truck transport has a lower impact on overall costs (12–16%) due to the shorter distances assumed for Ukraine compared to other countries.

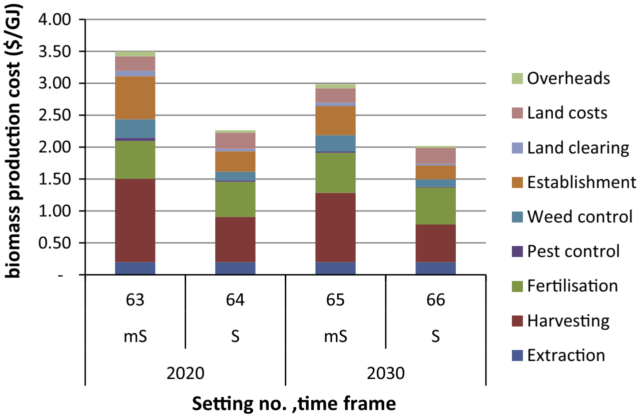

Fig. 12. Poplar production costs in Ukraine by component (mS = marginally suitable land, S = suitable land).

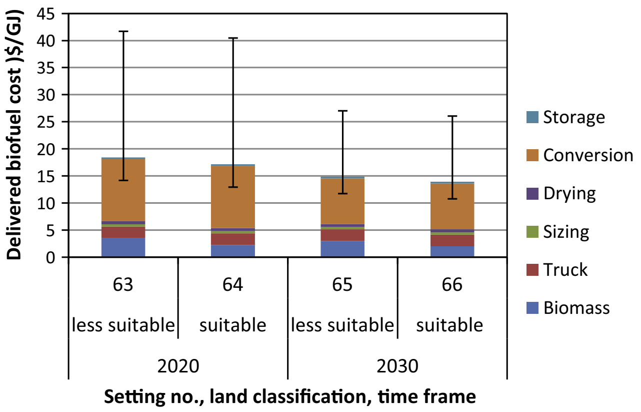

Fig. 13. Poplar to synfuel production costs (all Ukraine).

3.2.3. Switchgrass (next ethanol and synfuel production costs in Argentina)

Switchgrass is already being produced in Argentina and is mainly used for livestock forage production [98]. It is assumed that the switchgrass plantation is established on marginal soils using imported seeds and the plantation is expected to last a lifetime of 15 yrs before it is re-established. The productivity for switchgrass on marginal land is assumed to be 5 t_{dm}/ha/year. Future yield increases are estimated to be between 32% and 67% in 2030 compared to the current situation [44].

Land rent in Argentina ranges from 100 to 300 US$/ha/year depending on land suitability type and location. In 2030, land prices for marginal land remain constant; however for good quality land prices go up from 300 to 450 $/ha. Labour wages range from 2.18 to 3.18 $/h and in 2030; labour rates are expected to go up to between 3.98 and 8.29 $/h. Switchgrass seeds are imported from Texas at 20 US$/kg compared to a possible local production cost of only 10 US$/kg. Fertiliser costs in Argentina vary from 0.315 US$/kg (P) to 0.48 US$/kg (N) [99]. Aggregate switchgrass input production costs per hectare are shown in Table C13 in Appendix C.

Switchgrass production costs are calculated to be 3.2 $/GJ (306 $/ha) in 2020 and 3.0 $/GJ by 2030. See Fig. 14. The major cost elements in switchgrass production are machinery costs (37% short term and 44% for long term). Land costs are also significant (at 29% in 2020 and 36% in 2030). Fertiliser costs increase significantly from 3% in the short term to 12% in the long term.

A comparison of BtL and EtOH production from switchgrass in Argentina shows that EtOH production costs are marginally higher (18.5–21.0 $/GJ) compared to (18.3–20.8 $/GJ) for BtL. This is mainly attributed to the higher conversion efficiency for BtL, which offset the higher BtL investment costs. As shown in Fig. 15, conversion costs are dominant in the overall costs (43–52%) while truck

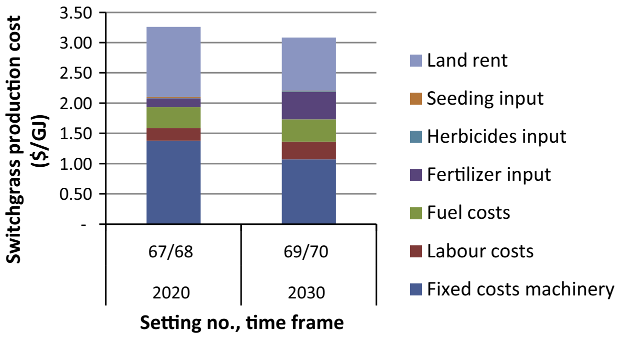

Fig. 14. Switchgrass production costs in Argentina by component (for EtOH (setting 67, 69) and BTL (setting 68, 70).

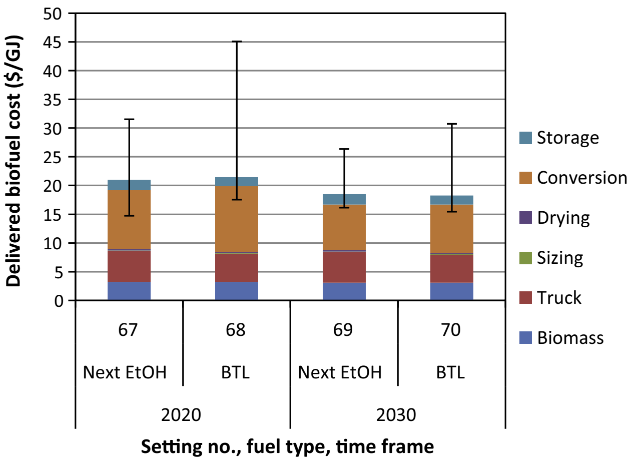

Fig. 15. Switchgrass to ethanol and synfuel production costs (all in Argentina).

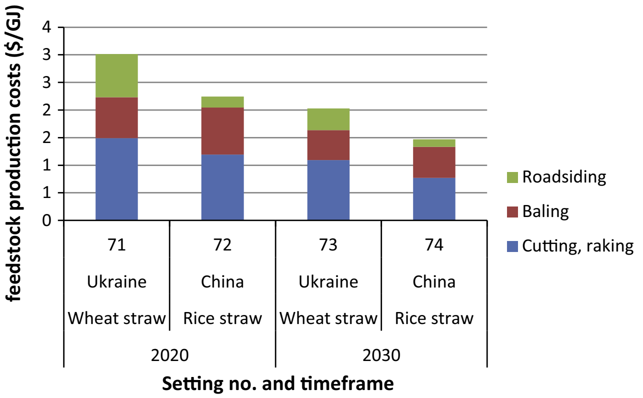

Fig. 16. Wheat and rice straw production costs in Ukraine and China by component.

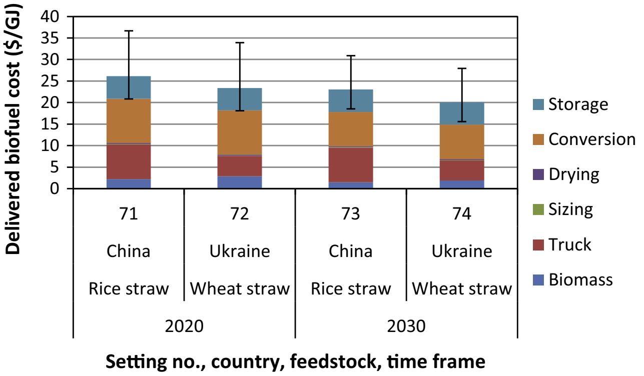

Fig. 17. Straw to EtOH production costs (China and Ukraine).

transport costs are also significant at 23–29%. Storage of switchgrass bales and produced fuel also contributes up to 10% of overall costs. Similarly, biomass production costs are also significant at 16%.

3.2.4. Rice and wheat straw (next ethanol production in China and Ukraine)

Rice and wheat straw have advantages as biomass feedstock because utilising them does not require recovering land costs, which are already covered in the grain enterprise [31]. The cost of the straw supply is taken as the opportunity cost of the agricultural residue at a grain plantation (usually taken as its fertiliser value or alternatively compared to the next application such as fodder) [28]. Cost elements include chopping/cutting/swathing, raking, baling and on-farm hauling of crop residues. Because unused residues may have value (in that they reduce fertiliser needs or soil erosion), appropriate adjustments must be included in cost estimates. However, estimating nutrient requirements is very site specific and needs detailed soil analysis to evaluate sustainable residue removal rates [31]. Due to lack of data in this case, we used a sustainable residue removal rate of 1 t_{dm}/ha/year estimated by SEC Biomass (2011) and we assume that nutrient compensation costs are negligible.

3.2.4.1. Wheat straw production in Ukraine. Table C14 (in Appendix C) shows the cost estimates for wheat straw collection and packaging in a typical Ukrainian facility. Sustainable wheat straw yields are estimated to be about 1 tons per ha at 15% moisture content [97].

The production cost of wheat straw is estimated to be 2.9 $/GJ in 2020 and 1.9 $/GJ in 2030. As shown in Fig. 16, cutting and raking wheat straw contributes nearly 50% of the total straw costs. Baling is also a significant cost adding another 25% to the overall costs while bale collection and forwarding (roadsiding) also contributes about 21%.

3.2.4.2. Rice straw in China. Production of rice straw also involves swathing, raking, baling and roadsiding as shown in Fig. 16 . Sustainable rice straw yield is assumed to be about 1 ton/ha. Rice straw is estimated to cost 2.2 $/GJ in 2020 and 1.5 $/GJ in 2030 at the farm gate in China. Swathing and baling dominate the overall costs at 43% and 38% respectively, both in the short term and long term. Raking and roadsiding contribute about 10% each.

Next generation ethanol production from straw is estimated to cost between 20 and 26 $/GJ in China and Ukraine. EtOH production from wheat straw in Ukraine is cheaper at 20–23 $/GJ compared to production from rice straw in China (23–26 $/GJ). The differences between the two countries can be attributed to the longer truck transport distances considered for China, which contribute 31–35% of the total costs compare to 20–23% for Ukraine. Contribution of conversion costs is comparable for the two countries at about 35–44%. As shown in Fig. 17, storage costs for straw bales and produced ethanol are also high, contributing between 20% and 26% of overall costs. Feedstock (straw) costs are relatively low compared to other cost elements (and other supply chains) at about 6–26%.

3.3. Overall cost overview 1st and 2nd generation biofuels

3.3.1. Comparison of biofuel production costs by feedstock type

Fig. 18 shows the total production cost ranges found for all first and second generation biofuels in all settings considered (including the uncertainty ranges for 2nd generation feedstocks).

The biofuel production costs in 2020 (1st gen.) and 2030 (2nd gen.) are lower than in 2010 (1st gen.) and 2020 (2nd gen.) in all cases. Out of all considered feedstocks, soy and palm biodiesel can be produced at lowest costs per GJ, between 6–10 $/GJ and 8–26 $/GJ respectively. Biofuel production from cassava (bioethanol) and jatropha (biodiesel) is comparatively more costly than other biofuel feedstocks and pathways and in many settings more expensive than fossil fuel (≈20–30 $/GJ). However, in 2020 increased yield and low labour costs could lead to competitive cassava and jatropha based biofuels production costs (around 15 $/GJ). Biofuel production from 2nd generation feedstock in the settings considered leads to costs between 13–45 $/GJ in 2020 and 11–31 $/GJ in 2030, of which eucalyptus based bioethanol has

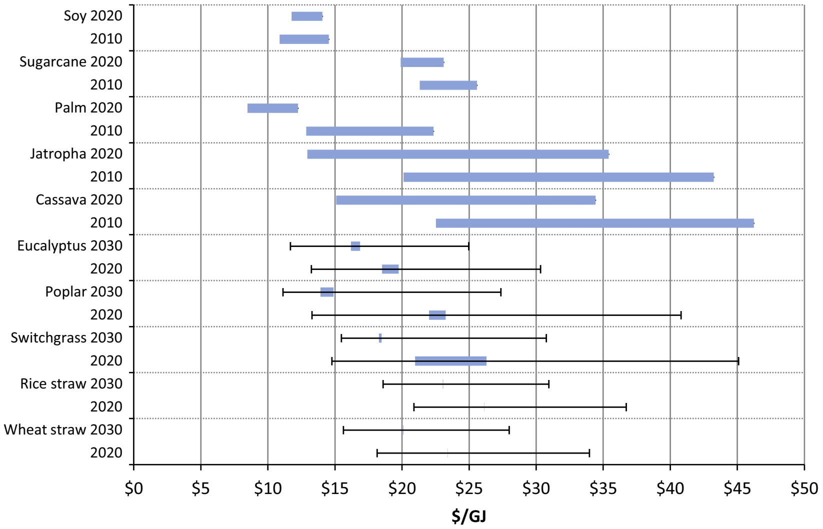

Fig. 18. Overview of biofuel production costs by feedstock type including all settings, 2010 and 2020, feedstock type and time frame on vertical axe.

the lowest costs (11–29 $/GJ) and switchgrass based biodiesel the highest (17.6–45 $/GJ) – for both the short and long term. For the base case, 2nd generation ethanol is more costly to produce (16–26 $/GJ) compared to 2nd generation biodiesel (14–21 $/GJ), but this depends strongly on assumed conversion costs, which are uncertain as shown by the ranges in costs. First and second generation biofuels do therefore not vary that much from each other. With the right setting all fuels could be produced for costs lower than current fossil fuel costs.

3.3.2. Comparison of biofuel production costs by region

Fig. 19 shows the biofuel production costs by country included in the analysis. The regions with the lowest production costs for first generation biofuels in 2010 are Argentina (soy biodiesel), Malaysia (Palm biodiesel) and Indonesia (Palm biodiesel). These regions are currently already large producers. In 2020, the same three regions still have low production costs, together with Colombia (Palm oil). The production of soy SVO is only taken into account in 2010, in 2020 it is assumed that Argentina only produces FAME. Thailand and India also offer promising perspectives, although the range in the case of India is quite large (due to the differences in yields for jatropha) which means there are quite some uncertainties (jatropha oil). In Mozambique, Mali and Tanzania, the production costs (of jatropha biodiesel) are lower in 2020 compared to 2010, there is still a large range.

For 2nd generation biofuels, production costs are much lower in Ukraine, due to the lower input costs reflected especially through the use of cheaper organic manure instead of chemical fertilisers in the production of poplar. However, the cost of fuel produced from wheat straw is high due to the higher logistical costs such as storage and truck transportation. Biofuel production costs in China are relatively higher than other countries due to the long

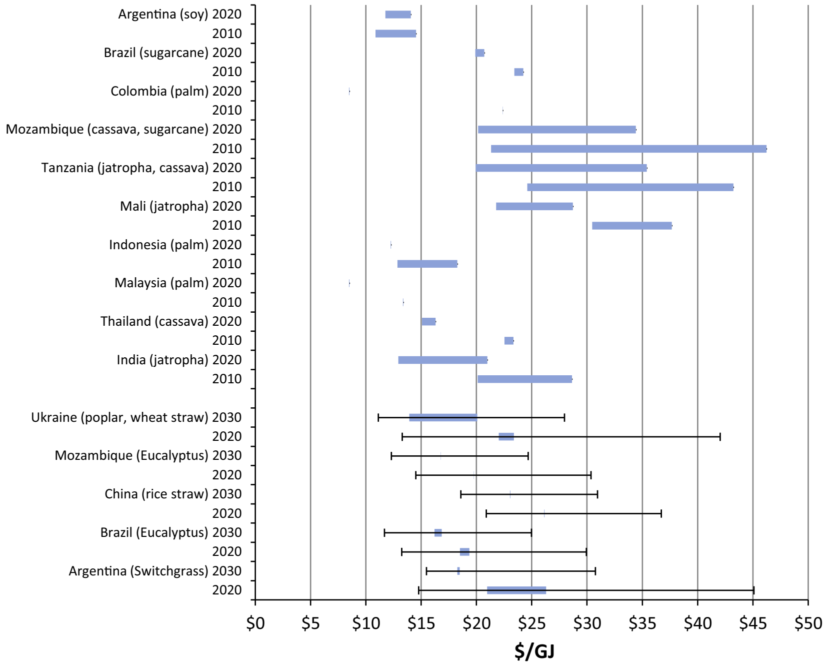

Fig. 19. Overview of biofuel production costs per region including ranges for 2nd generation crops, all settings combined (between brackets the biofuel feedstock base).

Table 6
Selected variation in parameters used in sensitivity analysis of 1st generation biofuels production.

Parameter	Variation	Original value
Discount rate (%)	6–15	8.2
Wage rate	1–15 $/h (soy)	Argentina: 3.18 $/h (2010) and 8.29 $/h (2020)
	0–500 $/ha/y (sugarcane)	Mozambique: 250 $/ha/y
	0–7.5 $/day (jatropha)	India: 1.29 $/day, Mali; 2.46 $/day and Tanzania: 2 $/day
	0–8 $/day (cassava)	Mozambique: 2 $/day (2010) 4 $/day (2020), Tanzania: 2 $/day (2010) and 4 $/day (2020), Thailand: 3.3–4.3 $/day

transportation distances of low energy density rice straw. This is due to low yields per ha and therefore large areas are required. Truck transportation contributes about 8 $/GJ to the overall fuel production costs in China. This demonstrates the need for reducing the energy density of agricultural residues by densification[8] of straw early in the chain to reduce the logistical costs.

3.4. Sensitivity analysis

For the 1st generation crops, discount rates and wage rates are varied (market price ranges and the response of the NPV for the raw feedstock are already discussed in earlier sections), and for 2nd generation crops we varied the technological learning and efficiency for conversion facilities, discount rate, and feedstock production costs.

3.4.1. 1st generation

We varied two parameters, the discount rate and the wage rate, see Table 6. In the Result section, the sensitivity of the NPV towards market prices has already been discussed.

Discount rates are varied from the original 8.2% to 6% and 15%, see Fig. 20.

The range for palm oil is now larger and goes up to 34 $/ha. The range for jatropha is even higher and varies from 12 to 47 $/ha. Still both cassava and jatropha have the largest range, while soy biodiesel (and palm) can be produced against the lowest costs.

Wages/labour costs: Wage rates for Argentina used in the calculations are 3.18 $/h in 2010 and set at 8.29 $/h in 2020. For this sensitivity analysis they are varied from 1 $/h to 15 $/h. Sugarcane labour costs are varied from zero to double (from 250 to 500 $/ha/yr in harvesting years). Palm lacks specific data on labour. Jatropha labour rates are varied from 0 to 7.5 $/day. The zero labour costs represent family labour. And finally for cassava the wage rates are varied from 0 to 8 $/day (8 is the double rate of the 4 $/day that is used for 2020 Moz.) (see Fig. 21).

The influence of wages is large especially for cassava ethanol, jatropha SVO and biodiesel (influences are only taken into account on labour changes in feedstock production stage). The influence on soy is minimal. The price of inputs has been considered constant.

3.4.2. 2nd generation

Advanced biofuel production costs depend on a number of factors as already shown by the differences among countries and feedstocks. For feedstock production, the feedstock productivity is important and developments in plant selection and breeding leading to experience/technological learning has a significant impact on future feedstock production costs. At the conversion stage, the capital investment cost and associated cost of capital are the key determinants of the biofuel production cost levels [83,100]. It is expected that future capital investment costs will decrease with technological learning and scaling up of production facilities [41], but this is uncertain. The variation of these factors is shown in Table 7.

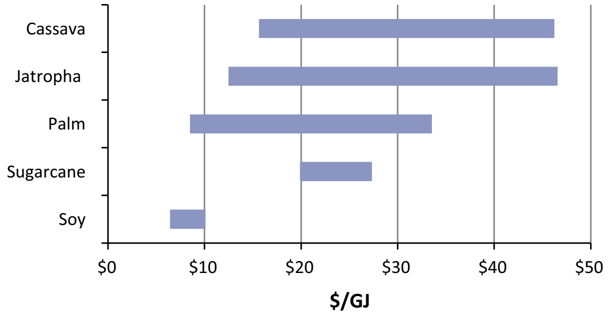

Fig. 20. New ranges for variation in discount rates, 6–15%.

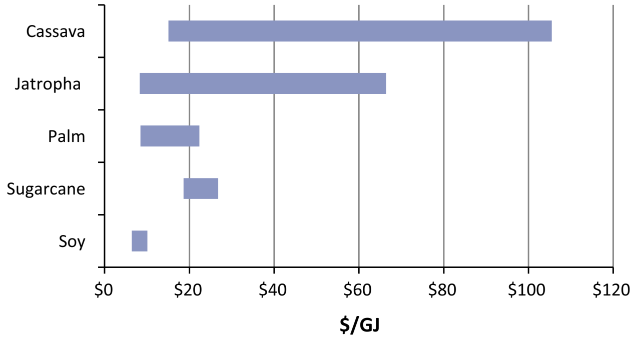

Fig. 21. New ranges for variation in wage rates, 1–15 $/h in Argentina, 0–500 $/ha/yr in Mozambique, jatropha labour rates 0–7.5 $/day and cassava 0–8 $/day.

The sensitivity analysis show large variations in potential fuel production from poplar (9.4–57.6 $/GJ) and switchgrass (12.8–61 $/GJ), (see Fig. 22). The economics of these supply chains are influenced by the future conversion efficiency improvements, which result in lower feedstock requirements and lead to corresponding decrease in logistical costs, especially long distance transport and long term storage of feedstock. All the supply chains are strongly influenced by conversion costs and the lower cost range reflects cheap cost of capital (i.e. 6%) and faster technological learning (progress ration of 0.88). Overall, biofuel production costs vary by 85% from about 10–60 $/GJ. The production costs of BtL vary over a much wider range from9.4–61 $/GJ, while 2nd generation ethanol production costs range from 9.8 to 47.6 $/GJ.

For comparison, recent state of the art analysis estimate that second generation production costs for bioethanol range from 13 to 30 US$/GJ, while BtL derived fuels are estimated to cost 16–30 US$/GJ [8]. The differences are mainly due to uncertainties in investment costs, feedstock types and technology configurations.

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[8] We assume straw is transported as bales from the field to the energy conversion facility. It is possible to further densify the straw into pellets or torrefied pellets before long distance transportation, but such options and alternative supply chains were not included in this study.

Table 7
Selected variation in parameter used in sensitivity analysis of 2nd generation biofuels production.

Parameter	Variation
Technological learning in conversion facilities (progress ratio)	0.88–0.98
Interest rate	6–15%
Conversion efficiency improvements	– EtOH from 35% to 45%: Base value – 40% – BtL from 40% to 50%: Base value – 45%
Variation in feedstock production costs	Labour increase to 319% in 2030; land rent by 50%; fertiliser by 300%; agrochemicals by 121%

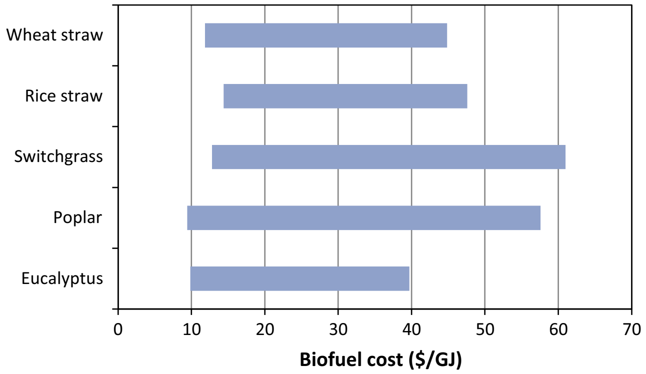

Fig. 22. Range in 2nd generation biofuel costs by feedstock type for both 2020 and 2030.

4. Discussion

This analysis only takes economic costs into account. Total availability, social and environmental effects are not taken into account. For this analysis we assumed that the biofuels value chains take into account basic sustainability criteria, which implies that the feedstock production does not result in deforestation, loss of biodiversity or competition with other land uses, which means environmental effects could be minimized and indirect land use change avoided. However, if a project is going to be implemented detailed socio-economic and environmental impact assessments are still required [7,101]. A more comprehensive approach would be to conduct a full impact analysis along the biofuel value chain. Meeting strict criteria may also affect biomass production costs to some extent, see Smeets and Faaij [34], this requires further research.

For first generation biofuels, prices of inputs are assumed to remain the same over the decade (2010–2020) across the biofuel value chain, but in reality several factors influence these prices. Indirect effects result from the price feedbacks of the economic system: once a commodity is increasingly used, and supply is constrained, prices tend to increase. Depending on the elasticity, the demand for that commodity will adjust to the new price, and this will in turn affect production levels, and hence, adjust prices again. A key issue in these feedbacks is the volatility of prices, i.e. their fluctuations, which can negatively affect both producers and consumers, especially for food and feed. Inflation could increase prices and revenues, while more efficient management techniques, better varieties, etc. could reduce prices. Also, fertiliser prices are linked to fossil prices that are highly volatile. The same accounts for the prices included in the NPV calculations for the feedstock production where current market prices are included. These can be highly volatile and will influence the profitability such as the market price for sugarcane that fluctuates with the global sugar prices. The indirect effects are difficult to model as only direct effects of price changes can be monitored, and cause-effect chains must be added to those. This means that indirect effects can be addressed adequately only through complex modelling which allows for (price) feedbacks, substitution, and market segmentation. This study does not carry out own modelling for that. More research is required to quantify these effects.

Second generation biofuel technologies represent an industry for which limited experience with commercial production yet exists [23]. A number of technological and economic challenges (especially in final biomass conversion) need to be overcome for the successful commercial deployment of these advanced bioenergy technologies [8,80,81]. For BtL, there is little commercial experience of integrating biomass gasification with FT processes [79]. Key BtL challenges relate to the process integration and optimisation as well as demonstration at industrial scale [8,82]. Similarly the key challenges for commercialising next ethanol include the development of low cost enzyme production, the development of robust microbes that can tolerate adverse process conditions, efficient conversion of all sugars, process integration and the demonstration of processes at industrial scale [8,18,80]. Significant progress is being made in RD&D though, and it is likely that commercial scale plants will be deployed by 2020 [8,81]. Second generation biofuel technology is capital intensive and cost effective at large scale [8,79]. Biomass production at such large scale requires mobilising large volumes of feedstock and therefore a key pre-requisite is that a large, stable supply of lignocellulosic biomass be guaranteed [81]. Also, investment in infrastructural development along the biomass supply chain needs to be realised especially in developing countries [83]. However, there are also opportunities for utilisation of agricultural and forestry by-products, which could lead to developing of new supporting industries and skills.

Due to the large number of settings and regions considered, there is also a large variation in the quality of the datasets employed to evaluate the economic performance of biofuel production for each setting. Generally, developing countries are poorly studied, and capacity for statistical data collection is lacking. Consequently the quality of data on land use, land quality, biomass resource potential, cost of factors of production, logistic costs, cost of technology and cost of capital is poor. Apart from labour and land costs, the costs of other factors of production are prone to fluctuations due to external shocks from the global markets [102]. Therefore, the uncertainty ranges are higher in developing economies than in industrialised countries. Future projections of costs of production in developing countries also contain even higher levels of uncertainty given the fragility of these economies. However, there are large differences between countries; for example countries such as Brazil, China and Ukraine have better developed datasets and their economies are more robust. For some countries, specific datasets are well developed. For example, biomass production in Mozambique is based on spatially explicit state of the art GIS modelling for both land productivity and transport logistics following van der Hilst et al. [5,33]. But future dynamics of various cost developments are difficult to model over time because of lack of sector specific studies and poor understanding of regarding future developments in these countries. As detailed in the methodology section, we have taken into account projected costs of various input elements in biomass production (such as labour, land rent, fuel costs), of which yield increases are the key driver of cost reduction. It is also important to note that yields will in reality vary, due to e.g. weather conditions, etc. For first generation biofuels, we used relative conservative yield estimates for 2020, considering documentation on higher yields that even can be obtained today (such as 25 FFB/year in Indonesia [59]. But yield increases can only be obtained when more knowledge is generated in developing countries and better and more efficient management systems are used.

Given the large number of settings and biofuel production pathways, comparison of the results from this study and literature cannot be succinctly captured in this discussion. Comparison of biofuel production costs is also further complicated by the different agro-ecological conditions and assumptions (e.g. management practices, inputs costs, exchange rates and discount factors) that are used in different studies [33].

We did not include a cost benefit assessment (NPV calculations) for 2nd generation feedstocks since the markets for these feedstocks are undeveloped or do not exist. Even for biomass feedstocks with a long history of production such as Eucalyptus, the production regime for current markets (mainly roundwood, poles, pulp and paper) is different from production targeting biomass for energy. Energy crop plantations are typically planted with higher stand densities and harvested over shorter cycles [26]. For residues, many studies use opportunity cost as an indicator of their potential value. The opportunity cost of using crop residues for energy is the value foregone by not using them in a competing application (or the price paid for residues by competing uses). For example, the residue market is expected to reflect the forage value of residue and prices for the close substitute, hay, when the unused residue is exhausted in a local area [28]. As the market develops, residue supply is expected to increase in value when all harvested residue is used by industry. This brings in complex market feedback dynamics which are difficult to model without employing for instance, Computable General Equilibrium models. Nevertheless, from the perspective of a 2nd generation biomass feedstock producer, the viability of biomass production becomes a question of choice between different feedstock types, whereby the feedstock offering higher returns on investment is preferred, also depending on market demands. We assume an efficient biomass production system which optimises the production inputs so as to deliver biomass at lowest possible production costs. For residues which are not currently being marketed, the only production costs are for collecting and baling the biomass at the farm and typically a profit margin as well as ‘farmer compensation’ for fertiliser value of biomass are included in the cost build up [31], ensuring the viability of the producer.

5. Conclusions and recommendations

High NPVs (meaning profitable production) are obtained for cassava (up to 16,000 US$/ha) and palm production (up to almost 7000 US$/ha). But there are also scenarios in which cassava yields a negative NPV, if yields are (very) low, which indicates that the project investment comes with risks of unprofitable production. The NPVs for jatropha range from −900 to 2000 US$/ha, while for sugarcane and soy the NPVs are positive in all analysed scenarios (2500–5000 US$/ha and 200–3000 $/ha respectively), these crops are also less sensitive towards changes in discount rates and wages and therefore these crops are expected to constitute a profitable investment. Main factors that influence the outcome of the NPV calculations are; yield, labour requirements, labour costs, land costs and the value of the by-products that are produced. High labour requirements can only be feasible with low wages, while a high level of inputs typically leads to an increased yield and therefore lower overall costs (except for jatropha). The price of the commodities is a key variable for the profitability of the project. Several crops such as palm and sugarcane have different markets they can supply, e.g. food, fuel, paper, etc., sometimes even at the same time such as for soy (biodiesel and soy meal). This means the producer can choose the market with the highest price. In addition, the value of the fuel in relation to the oil price is important, in many cases this can result in good NPVs. On the other hand, the costs of biofuels will also depend on the price of the commodity in the other market, and this could also increase costs.

Results from the current study can be used as benchmark, to identify the ranges in cost prices of 1st and 2nd generation feedstocks per region. Total biofuel production costs in 2010 are estimated to vary from 10 to 45 US$/GJ for 1st generation feedstocks in the chosen settings, and from around 10–35 US$/GJ in 2020, compared to 20–30 US$/GJ for fossil fuels. Argentina and Malaysia are the regions with the lowest production costs for biofuel (soy and palm biodiesel for 10–14 US$/GJ and 8–23 US$/GJ respectively), although potential for cost reduction exists in other regions. Cassava and Jatropha are very sensitive towards changes in wage rates, the production costs range from US$/GJ 14 to over 100 US$/GJ if wage rate is varied. Production costs of 2nd generation biofuels are estimated to be 17–26 US$/GJ in 2020 and 14–23 US$/GJ in 2030. BtL production costs range between 14 and 21 $/GJ while advanced EtOH costs 16–26 $/GJ. Poplar based synfuel production in Ukraine has the lowest costs (14–17 US$/GJ) and rice straw based bioethanol the highest (23–26 US$/GJ) – for both the short and long term.

The costs ranges (including uncertainty ranges) of 2nd generation feedstocks are high, but they are within similar cost ranges as for 1st generation feedstocks. The pay-back time on investment, as well as the size of investment and the alternative commodity markets, varies with the type of feedstock. The choice of suitable feedstock therefore depends on the local agricultural system, and the preferences and means of the local farmers. Key to the competitive production of 2nd generation fuels is the optimisation of the conversion process, which dominates overall production costs (with 35–65% of total costs). Also important is the efficient organisation of supply chain logistics; especially for the low energy density feedstocks such as wheat straw, the handling, storage and transportation requires densification of the feedstock early in the chain to reduce subsequent step costs. For wheat and rice straw, storage costs account for up to 20% while their truck transportation accounts for up to 35% of the total supply chain costs. Feedstock production costs are also important for the selected energy crops, feedstock costs account for 20% of total costs for eucalyptus and poplar, and 16% for switchgrass. In addition to conversion costs, agricultural efficiency, and biomass yields are found to be key determinants of economic viability.

The differences in the biofuel production costs for the fuel production pathways indicate the importance of using specific settings that take into account local circumstances. Implementation of a project should also depend on comparing NPVs and total production costs to alternatives in the region.

A mayor difference between the feedstocks is the type of investment that is required for cultivation. Perennials such as Palm or Eucalyptus require several years before the first benefits can be obtained, these first years need to be overcome with other means of income. Furthermore, some annual crops such as soy, require more upfront capital investment in machinery and are therefore less suitable for small scale farmers with little income. On the other hand, there are crops that can be planted as additional (or side-) crop such as jatropha, but a reasonable income from this crop alone is unlikely. The different feedstocks should therefore be implemented in the local agricultural system according to the preferences and means of the local farmers.

6. Recommendations

Local data collection and specific case studies are key to more accurate modelling of the biofuel production costs, the profitability for a farmer (by means of NPV calculations) and the identification of alternatives.

Various cost factors should be taken into consideration when analysing the feasibility of biofuels. Costs are dynamic and long term costs should be considered indicative. Generally production costs are expected to decrease over time following continuous process improvements, technological learning and increasing scale of production. Possibilities for cost reduction can also be linked to local technology adaptation and strategies need to be developed to identify technology components that can be locally fabricated. The cost of energy sources (for example fossil diesel fuel for usage in a diesel generator in a remote village) determines the competitiveness of the biofuel and should be considered as well.

Appropriate policies need to be devised to make biofuels production more competitive and reduce investment risks. Key sustainability aspects should be fully taken into account in these policies, when assessing biofuel supply. Studies have shown that inclusion of sustainability criteria has potential impacts on the amount of biofuels that can be produced as well as final delivered costs of the biofuels [34]. A prerequisite is that sufficient data of high quality is available.

When the NPV is close to zero, there is an expected no-profit no loss scenario, then further research into the financial viability by an extended Cost Benefit analysis is recommended, including other indicators such as, Internal Rate of Return (IRR), Benefit/Cost Ratio (BCR) and Pay Back Period (PBP).

Given the status of the technology and investment requirements to establish processing plants, it is unlikely that large scale second generation biofuels production can be realised in developing countries in the coming decade. However, developing countries can already develop a biofuel feedstock production industry, which could be the basis for a strong biofuel industry when the technology matures. Investment in feedstock production could offer an option for developing countries to profit from the growing biomass market for second-generation biofuel production outside their borders, provided that transport infrastructure is suitably developed and key socio-economic and environmental sustainability frameworks are institutionalised. As a next step, cooperation on R&D at a scientific level, skills development and adaptation of technology would be needed in developing countries to build capacity for second-generation biofuel production. Similarly, investment strategies need to be developed and piggybacking on existing industries (such as forestry) could be one route to over-coming the project finance barriers.

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Appendix A

See Table A1.

Table A1
Specification of all 74 settings used in the research.

No	Crop	Country	Smallholder/plantation	Management system	End product	Timeframe	Byproducts
1	Soy	Argentina	Smallholders	Low mechanisation, no tillage	SVO	2010	Animal feed
2	Soy	Argentina	Smallholders	No mechanisation, no tillage	FAME	2010	Animal feed
3	Soy	Argentina	Plantation	High rate of mechanisation, tillage	FAME	2010	Animal feed
4	Soy	Argentina	Plantation	High rate of mechanisation, no tillage	FAME	2010	Animal feed
5	Soy	Argentina	Plantation	High inputs (irrigation), no tillage	FAME	2020	Animal feed
6	Soy	Argentina	Plantation	high rate of mechanisation, tillage	FAME	2020	Animal feed
7	Soy	Argentina	Plantation	High rate of mechanisation, no tillage	FAME	2020	Animal feed
8	Sugarcane	Brazil	Centralised system (with outgrowers)	Mechanised harvesting, no irrigation (intermediate inputs)	EtOH	2010	Surplus bagasse into electricity
9	Sugarcane	Brazil	Centralised system (with outgrowers)	Manual harvesting, irrigation (high inputs)	EtOH	2010	Surplus bagasse into electricity
10	Sugarcane	Brazil	Centralised system (with outgrowers)	Mechanised harvesting, irrigation	Next EtOH	2020	Surplus bagasse into next EtOH
11	Sugarcane	Mozambique	Centralised system (with outgrowers)	No irrigation (intermediate inputs)	EtOH	2010	Surplus bagasse into electricity
12	Sugarcane	Mozambique	Centralised system (with outgrowers)	Irrigation (high inputs)	EtOH	2010	Surplus bagasse into electricity
13	Sugarcane	Brazil	Centralised system (with outgrowers)	Mechanised harvesting, no irrigation (intermediate inputs)	EtOH	2020	Surplus bagasse into electricity

(continued on next page)

Table A1 (*continued*)

No	Crop	Country	Smallholder/plantation	Management system	End product	Timeframe	Byproducts
14	Sugarcane	Brazil	Centralised system (with outgrowers)	Mechanised harvesting, irrigation (high inputs, high rate mechanisation)	EtOH	2020	Surplus bagasse into electricity
15	Sugarcane	Brazil	Centralised system (with outgrowers)	Mechanised harvesting, irrigation (high inputs, high rate mechanisation)	Next EtOH	2030	Surplus bagasse into next EtOH
16	Sugarcane	Mozambique	Centralised system (with outgrowers)	No irrigation (intermediate inputs)	EtOH	2020	Surplus bagasse into electricity
17	Sugarcane	Mozambique	Centralised system (with outgrowers)	Irrigation (high inputs)	EtOH	2020	Surplus bagasse into electricity
18	Palm	Indonesia	Smallholders	Intermediate inputs	SVO	2010	No pome use
19	Palm	Indonesia	Smallholders	Intermediate inputs	FAME	2010	No pome use
20	Palm	Indonesia	Plantation	High inputs	FAME	2010	No pome use
21	Palm	Colombia	Smallholders	Intermediate inputs	FAME	2010	No pome use
22	Palm	Malaysia	Plantation	High inputs	FAME	2010	No pome use
23	Palm	Indonesia	Plantation	High inputs	FAME	2020	Pome use
24	Palm	Malaysia	Plantation	High inputs	FAME	2020	Pome use
25	Jatropha	Tanzania	Smallholders	Low inputs, marginal land, no irrigation	SVO	2010	Seedcake as fertiliser
26	Jatropha	Tanzania	Plantation	High inputs, good land, no irrigation	FAME	2010	Seedcake as fertiliser, shells as fuel
27	Jatropha	Tanzania	Plantation	Intermediate inputs, marginal land, no irrigation	FAME	2010	Seedcake as fertiliser, shells as fuel
28	Jatropha	Tanzania	Smallholders	Low inputs, marginal land, no irrigation	FAME	2010	Seedcake as fertiliser, shells on field
29	Jatropha	Tanzania	Smallholders	Smallholder, intermediate inputs, marginal land	FAME	2010	Seedcake as fertiliser, shells on field
30	Jatropha	Mali	Smallholders	Low inputs	FAME	2010	Seedcake as fertiliser, shells on field
31	Jatropha	Mali	Smallholders	Intermediate inputs	FAME	2010	Seedcake as fertiliser, shells on field
32	Jatropha	India	Smallholders	Low inputs	FAME	2010	Seedcake as fertiliser, shells on field
33	Jatropha	India	Smallholders	Intermediate inputs	FAME	2010	Seedcake as fertiliser, shells on field
34	Jatropha	Tanzania	Plantation	High inputs, good land, no irrigation	FAME	2020	Seedcake as fertiliser, shells as fuel
35	Jatropha	Tanzania	Plantation	Intermediate, marginal land, no irrigation	FAME	2020	Seedcake as fertiliser, shells as fuel
36	Jatropha	Tanzania	Smallholders	Low inputs, marginal land	FAME	2020	Seedcake as fertiliser, shells on field
37	Jatropha	Tanzania	Smallholders	Intermediate inputs, marginal land	FAME	2020	Seedcake as fertiliser, shells on field
38	Jatropha	Mali	Smallholders	Low inputs	FAME	2020	Seedcake as fertiliser, shells on field
39	Jatropha	Mali	Smallholders	Intermediate inputs	FAME	2020	Seedcake as fertiliser, shells on field
40	Jatropha	India	Smallholders	Low inputs	FAME	2020	Seedcake as fertiliser, shells on field
41	Jatropha	India	Smallholders	Intermediate inputs	FAME	2020	Seedcake as fertiliser, shells on field
42	Cassava	Mozambique	Smallholders	Low inputs (see table for definition)	EtOH	2010	(electricity mix difference between countries)
43	Cassava	Mozambique	Smallholders	Intermediate inputs	EtOH	2010	
44	Cassava	Tanzania	Smallholders	Low inputs	EtOH	2010	
45	Cassava	Tanzania	Smallholders	Intermediate inputs	EtOH	2010	
46	Cassava	Thailand	Smallholders	Low inputs	EtOH	2010	
47	Cassava	Thailand	Smallholders	Intermediate inputs	EtOH	2010	
48	Cassava	Mozambique	Smallholders	Low inputs	EtOH	2020	
49	Cassava	Mozambique	Smallholders	Intermediate inputs	EtOH	2020	
50	Cassava	Mozambique	Plantation	High inputs	EtOH	2020	
51	Cassava	Tanzania	Smallholders	Low inputs	EtOH	2020	
52	Cassava	Tanzania	smallholders	intermediate inputs	EtOH	2020	
53	Cassava	Tanzania	Plantation	High inputs	EtOH	2020	
54	Cassava	Thailand	Smallholders	Low inputs	EtOH	2020	
55	Cassava	Thailand	Smallholders	Intermediate inputs	EtOH	2020	
56	Cassava	Thailand	Plantation	High inputs	EtOH	2020	
57	SRC Eucalyptus	Mozambique	Plantation	Less suitable land, well managed plantation, no irrigation	Next EtOH	2020	
	SRC Eucalyptus	Mozambique	Plantation	Less suitable land, well managed plantation, no irrigation	Solid		
58	SRC Eucalyptus	Brazil	Plantation	Less suitable land, well managed plantation, no irrigation	Next EtOH	2020	
59	SRC Eucalyptus	Brazil	Plantation	Suitable land, well managed plantation, no irrigation	Next EtOH	2020	
60	SRC Eucalyptus	Mozambique	Plantation	Less suitable land, well managed plantation, no irrigation	Next EtOH	2030	

Table A1 (*continued*)

No	Crop	Country	Smallholder/plantation	Management system	End product	Timeframe	Byproducts
61	SRC Eucalyptus	Brazil	Plantation	Less suitable land, well managed plantation, no irrigation	Next EtOH	2030	
62	SRC Eucalyptus	Brazil	Plantation	Suitable land, well managed plantation, no irrigation	Next EtOH	2030	
63	SRC poplar	Ukraine	Plantation	Less suitable, well managed plantation, no irrigation	BTL	2020	
64	SRC poplar	Ukraine	Plantation	Suitable, well managed plantation, no irrigation	BTL	2020	
65	SRC poplar	Ukraine	Plantation	Less suitable, well managed plantation, no irrigation	BTL	2030	
66	SRC poplar	Ukraine	Plantation	Suitable, well managed plantation, no irrigation	BTL	2030	
67	Switchgrass	Argentina	Plantation	Less suitable land, well managed plantation, no irrigation	Next EtOH	2020	
68	Switchgrass	Argentina	Plantation	Less suitable land, well managed plantation, no irrigation	BTL	2020	
69	Switchgrass	Argentina	Plantation	Less suitable land, well managed plantation, no irrigation	Next EtOH	2030	
70	Switchgrass	Argentina	Plantation	Less suitable land, well managed plantation, no irrigation	BTL	2030	
71	Rice straw	China			Next EtOH	2020	
72	Wheat straw	Ukraine			Next EtOH	2020	
73	Rice straw	China			Next EtOH	2030	
74	Wheat straw	Ukraine			Next EtOH	2030	

Appendix B

B.1. Input data for Soy

See Table B2.

B.2. Input data for Sugarcane

See Table B3.

Table B2
Input data used in calculations soy settings 1–7.

Country	Unit	Argentina	Argentina	Argentina	Argentina	Argentina	Argentina	Argentina	Source
Setting No.		1	2	3	4	5	6	7	
System		Smallholders	Smallholders	Plantation	Plantation	Plantation	Plantation	Plantation	
Mechanisation		Low	Low	High	High	High (irrigation)	High	High	
Tillage		No	No	Yes	No	No	Yes	No	
Endproduct		SVO	FAME	FAME	FAME	FAME	FAME	FAME	
Year		2010	2010	2010	2010	2020	2020	2020	
Yield	t/ha	2.8	2.8	3.6	4.5	4	4	5	[46]
Province		South of oba (rio Cuarto)	South of Cordoba (rio Cuarto)	Pergamino and Pehuajo (North and West of BA)	South of Santa Fe (Venado Tuerto)				
t dry per ton fresh		0.865	0.865	0.865	0.865	0.865	0.865	0.865	
Yield dry	T (dry)/ha	2.51	2.42	3.11	3.89	3.46	3.46	4.33	
Transport distance field-processing unit	km	400	400	140	190	140	140	190	[46]
Transport distance SVO to filling station	km	150	150	150	150	150	150	150	Est. IFEU
Discount factor		8.2	8.2	8.2	8.2	8.2	8.2	8.2	[21]
Price soy beans	US$/ton	168.82	168.82	168.82	168.82	168.82	168.82	168.82	[46]
Transport costs	US$/ton km	$0.06	$0.06	$0.06	$0.06	$0.06	$0.06	$0.06	[44]
Crushing	US$/ton grain	$12	$12	$12	$12	$5	$5	$5	[44]
Allocation to oil	%	20%	20%	20%	20%	20%	20%	20%	
Density	Ton/l	0.000892	0.000892	0.000892	0.000892	0.000892	0.000892	0.000892	[44]
Energy content biodiesel	GJ/l	0.032728							

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Table B2 (*continued*)

Country	Unit	Argentina	Argentina	Argentina	Argentina	Argentina	Argentina	Argentina	Source
Conversion costs biodiesel	US$/l	$0.00	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	[44]
Wage rate	US$/h	$3.18	$3.18	$3.18	$3.18	$8.29	$8.29	$8.29	[44]
Ton grains per ton oil		5.897	5.897	5.897	5.897	5.897	5.897	5.897	[44]
Seeds	US$/ha	$32.64	$32.64	$45.70	$45.70	$45.70	$45.70	$45.70	[44]
Herbicides	US$/ha	$93.66	$93.66	$113.87	$113.87	$113.87	$113.87	$113.87	[44]
Insecticides	US$/ha	$50.10	$50.10	$75.50	$75.50	$75.50	$75.50	$75.50	[44]
Fertilizers	US$/ha	$29.7	$29.7	$102.60	$102.60	$102.60	$102.60	$102.60	[44]
	US$/ha	$3.00	$3.00	$3.00	$3.00	$3.00	$3.00	$3.00	[44]
Labour input	US$/ha	$4.87	$4.87	$2.83	$2.83	$7.24	$7.24	$7.21	[44]
Fuel input	US$/ha	$8.21	$8.21	$13.30	$13.30	$13.30	$13.30	$13.57	[44]
O&M	US$/ha	$9.71	$9.71	$11.74	$11.74	$11.74	$11.74	$11.74	[44]
Harvesting costs	US$/ha	$43.20	$41.71	$43.20	$43.74	$43.74	$43.74	$54.68	[44]

Table B3
Input data used in calculations for sugarcane settings 8–17.

Setting number	Unit	8	9	10	11	12	13	14	15	16	17	Source
Country		Brazil	Brazil	Brazil	Mz	Mz	Brazil	Brazil	Brazil	Mz	Mz	
Year		2010	2010	2020	2010	2010	2020	2020	2030	2020	2020	
Yield	kg/ha	60	90	90	76	100	63	94.5	94.5	79.8	105	[6,50,51]
Sugarcane field to ethanol factory	km	50	50	50	50	50	50	50	50	50	50	IFEU est [7]
Ethanol factory to filling station	km	200	200	200	200	200	200	200	200	200	200	IFEU est [7]
Transport costs	$/ton km	0.035	0.035	0.035	0.096	0.096	0.035	0.035	0.035	0.096	0.096	[6,52]
Conversion to ethanol	$/m^3	164.27	164.27	164.27	164.27	164.27	113	113	113	113	113	[36]
Land rent	$/ha				22	22				22	22	[51]
Land clearing	$/ha				1350	1350				1350	1350	[51]
Planting												
Seeds	$/ha				357	357				357	357	[103]
Land preparation	$/ha				398	398				398	398	
Cultivation labour	$/ha				27	27				27	27	
Cultivation chemicals	$/ha				115	115				115	115	
Cultivation fertiliser	$/ha				231	231				231	231	
Cultivation mechanized	$/ha				150	150				150	150	
Ratoon cultivation												[103]
Labour	$/ha				248	248				248	248	
Pesticide/Herbicide	$/ha				115	115				115	115	
Fertiliser	$/ha				219	219				219	219	
Mechanized (tractors, ripeners)	$/ha				194	194				194	194	
Irrigation	$/ha				0	604				604	604	[51]
Instalment	$/ha				0	2697				2697	2697	
Labour	$/ha				0	182				182	182	
Maintenance	$/ha				0	106				106	106	
Electricity	$/ha				0	245				245	245	
Bulk supply	$/ha				0	72				72	72	
Harvest and delivery												
Harvest	$/ton				9	9				9	9	[103]
Market price sugarcane	$/ton				35	35				35	35	[54]

Note: all data for Brazil is based on [6] (all $ are US$$_{2010}$).

B.3. Input data for Palm

See Tables B4 and B5 and Fig. B1.

B.4. Input data for Jatropha

See Table B6.

B.5. Input data for Cassava

See Tables B7 and B8.

Appendix C. Second generation biofuels

C.1. Feedstock production and supply

The development of second generation energy crop plantations involves four major phases: site preparation, planting, maintenance and harvesting. Specific activities at each stage depend on the site quality which influences the degree of site preparation that is necessary; choice of species, planting density, and rotations; required cultural management and soil amendments (fertilisation, weed control, animal control, and pest management); as well as transport and logistics.

Table B4
Input data used in calculations for palm oil settings 18–24.

Country	Unit	Indonesia	Indonesia	Indonesia	Colombia	Malaysia	Indonesia	Malaysia	Colombia	Source
Setting nr		18	19	20	21	22	23	24	21b	
Endproduct		SVO	FAME	FAME	FAME	FAME	FAME	FAME	FAME	
Year		2010	2010	2010	2010	2010	2020	2020	2020	
Yield FFB	t/ha	16	16	17	18	19	19	19	19	IFEU/UU
Transport plantation to mill	km	7	75	75	75	75	75	75		[45]
Mill to refinery	km	200	200	200	200	200	200	200		
Refinery to end user	km	200	200	200	200	200	200	200		
kg FFB's per liter SVO (OER)		4.76			4.76					
Price FFB	$/kg	$0.15	$0.15	$0.15						[32]
Price FFB	$/ton	$152.97	$152.97	$152.97	$152.97	$60.17				[32,58]
Transport costs FFB	$/ton km	$2.24	$2.24	$2.24	$0.11					[45,104]
Transport costs oil	$/ton km				$0.06					_ENREF_21[104]
Production CPO per ton	$/ton				35.23					
Refining and esterification	$/l		0.20	0.20	0.20	0.20	0.02	0.02	0.20	
Wages agricultural sector	$/day	$3	$3	$3	$7		$3			Laboursta
Exchange rates		IDR 8.910			CLP 1.966	MYR 3.13	IDR 8.910			www.oanda.com

Table B5
Input data for setting 21, palm production in Colombia in discounted $/ha [32].

	21 Colombia
Total inputs	$5.797
Seed/seedlings	$300
Fertilizers	$4.633
Phytosanitary control	$74
Weed control	$50
Other supplies	$740
Total labour	$3.122
Nursery and planting	$74
Fertilisation	$198
Phytosanitary control	$360
Weed control	$508
Harvest	$1.847
Other activities	$134
Transport	$522
Total maintenance	$1.263
Equipment	$271
Animals	$77
Infrastructure	$915
Total fixed capital	$2.410
Land rent	$0
Administration costs	$1.580
Total	$14.693

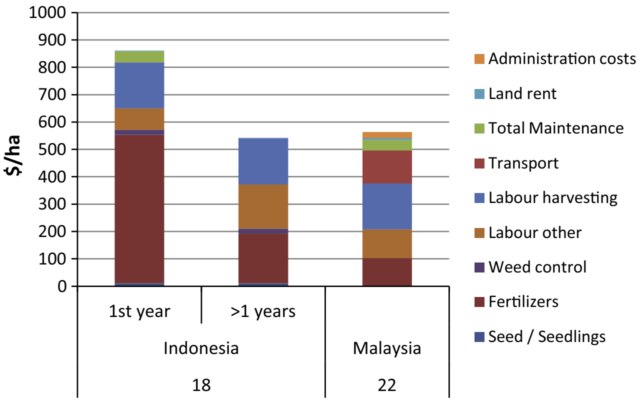

Fig. B1. Input data palm FFB production in Indonesia and Malaysia [45,58].

Eucalyptus production costs in Brazil and Mozambique: Table C9 shows the eucalyptus production cost inputs in Mozambique.

Future changes in feedstock production cost – Long term pressure on land is expected under a business as usual scenario and thus the cost for land is likely to increase, pushing up biomass production costs. Similarly, as Mozambique's economy grows, it is expected that labour wages will increase. When labour costs increase, efficient machinery will become more attractive. Energy input costs are also expected to grow, but with improving infrastructure, diesel distribution costs could go down. When diesel prices go up, full mechanisation will be less attractive. In the future, improved seeds and breeding as well as technological learning about seed technology are expected to result in higher biomass yields which will result in decreasing production costs. Globally, fertiliser prices will increase due to higher fossil fuel prices and to P fertiliser scarcity. Locally, prices could go down when there is critical mass for the establishment of domestic production. All these factors are expected to have varied impacts on the biomass production costs, but increase in yields is likely to have a much bigger impact on overall costs – and thus future costs are expected to decrease.

Eucalyptus production costs in Brazil – For Brazil, eucalyptus production costs are estimated using a set of assumptions shown in Table C11. For the different soil qualities, the required amount of fertiliser and corresponding biomass yields are shown in Table C10.

Poplar production costs in Ukraine: Table C12 shows the corresponding amounts of input requirements by land suitability.

Switchgrass production costs in Argentina: Table C13 shows the input requirements for switchgrass production in Argentina in 2020 and 2030.

Rice and wheat straw production: Table C14 shows the cost estimates for wheat straw collection and packaging in a typical Ukrainian facility.

C.2. Second generation biofuels – supply chain analysis

Biomass energy supply chains start with the feedstock production until final biomass fuel is delivered in the market. The number of intermediate stages in a chain varies depending on the feedstock characteristics, pretreatment requirements and infrastructure. More detailed discussion on second generation bioenergy supply chains is given in Batidzirai et al. [83]. Biofuel production costs include feedstock production costs, pretreatment costs, transport costs, storage costs and conversion costs. The costs that are analysed here are very generic, in the sense that it is important to include spatial detail and biomass distribution detail to come up with more representative estimates. However, country specific information is also included, such as expected transport distances and truck transport limitations as well feedstock production costs. See Table C15.

Table B6
Input data used in calculations for jatropha settings 25–41 (the settings 25–33 are shown in detail, the settings 34–41 are all based on 2020 and are similar unless noted otherwise).

Setting number	Unit	25	26	27	28	29	30	31	32	33	34–41	Source
Country		Tanzania	Tanzania	Tanzania	Tanzania	Tanzania	Mali	Mali	India	India	2020	
Yield	kg/ha	1100	3000	2500	1100	1980	1000	1500	2000	2500	+15%	
Land rent	US$	20	20	20	20	20	0	0	$19.92	$19.92		[21,65,105]
Market price	$/kg	$0.14	$0.14	$0.14	$0.14	$0.14	$0.11	$0.11	$0.19	$0.19		
Wage rate	$/day	$2.00	$2.00	$2.00	$2.00	$2.00	$2.46	$2.46	$1.29	$1.29		
Harvest efficiency	kg/person/day	40	40	40	40	40	40	40	40	40		
Conversion costs	$/l	$0.20	$0.20	$0.20	$0.20	$0.20	$0.20	$0.20	$0.14	$0.14	$0.02	
Distribution costs	$/l	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	
Transport from field to processing unit	km	450	190	190	450	450	450	450	450	450		
Transport from processing to filling station	km	200	200	200	200	200	200	200	200	200		
Price per km (10t)	$/ton km	$0.096	$0.096	$0.096	$0.096	$0.096	$0.096	$0.096	$0.030	$0.030		

Data Tanzania: [21,106] (conversion −0.03 $/l due to glycerine sales).
Data Mali: [107], land: [105], Wages: [70], market prices seed: personal communication Ard Lengkeek (Mali Biocarburant).
Data India: [65,69].
Labour requirements for Jatropha cultivation and inputs and costs are based on [21]. Transesterification costs are 0.25 $/l for the 2010 settings based on Van Eijck et al. [21], and 0.15 $/l for the settings in 2020, based on Mulugetta [20].
Land rent is 20 $ per ha per year.

Table B7
Yield levels for cassava.

Setting number	Input system	Yield (t/ha)	Region	Literature source
42	Low inputs	4	Mozambique	FAO average
43	Intermediate inputs	6	Mozambique	FAO average
44	Low inputs	6	Tanzania	[21]
45	Intermediate inputs	12	Tanzania	[21]
46	Low inputs	20	Thailand	[77][a]
47	Intermediate	22	Thailand	[77][a] average of country averages 2007–2009
54	Low	32	Thailand	[78][a]
55	Intermediate	34	Thailand	[78]
56	High	44	Thailand	Estimate IFEU/UU

[a] Also based on personal communication Prof. Gheewala, Bangkok, Thailand.

Table B8
Input data used in calculations for cassava settings 42–56 (the settings 42–47 are shown in detail, the settings 48–56 are all based on 2020 and are similar unless noted otherwise).

Country	Unit	Mozambique	Mozambique	Tanzania	Tanzania	Thailand	Thailand	
Setting nr		42	43	44	45	46	47	48–56
System		Smallholders	Smallholders	Smallholders	Smallholders	Smallholders	Smallholders	
Inputs		Low	Intermediate	Low	Intermediate	Low	Intermediate	
Year		2010	2010	2010	2010	2010	2010	2020
Yield	t/ha	4	6	6	12	20	22	
Transport distance field-chips	km	10	10	10	10	10	10	
Transport distance chips-ethanol	km	100	100	100	100	100	100	1
Transport distance ethanol-distribution	km	200	200	200	200	200	200	
Discount factor	%	8.20%	8.20%	8.20%	8.20%	8.20%	8.20%	
kg roots per litre ethanol	kg/l	7.5	7.5	7.5	7.5	7.5	7.5	
Average wage in agricultural sector	$/day	2	2	2.00	2	3.3–4.3	3.3–4.3	$4.00
Price fresh roots	$/ton	$58	$58	$91	$91	$45	$45	
Transport costs	$/ton km	0.096						
Costs								
Land preparation	$/ha	$60	$60	$60	$60	70	$70	
Plantation	$/ha	$58	$58	$58	$58	32	$32	
Treatment	$/ha	$62	$108	$62	$108	41	$81	
Harvesting	$/ha	$104	$104	$104	$104	91	$91	
Labour costs	$/ha	284	330	284	330	233	$233	
Varieties/stakes	$/ha	$10	$10	$10	$10	$42	$42	
Fertilizers	$/ha		$52		$52	$33	$675	
Herbicide & Insecticide	$/ha		$21		$21	$16	$32	
Fuels and lubricant	$/ha					$0.72	$1.44	
Agricultural materials and auxiliaries	$/ha	$18	$18	$18	$18	$0.46	$0.93	
Maintenance costs	$/ha					$0.31	$0.31	
Material cost	$/ha	$28	$101	$28	$101	$93	$93	

Table B8 (*continued*)

Country	Unit	Mozambique	Mozambique	Tanzania	Tanzania	Thailand	Thailand
Interest						$32	$32
Land rental costs	$/ha	$20	$20	$20	$20	$57	$57
Depreciation costs for agricultural machines	$/ha					$1.65	$1.65
Interest for agricultural machinery	$/ha					$0.21	$0.21
Fixed costs	$/ha					$59	$59
Total	$/ha	$48	$121	$48	$121	$184	$184
Total incl labour	$/ha	$332	$451	$332	$451	$417	$417

Table C9
Cost elements for eucalyptus production in Mozambique. *Source:* [51,84,108].

Cost Item	Description
Land	Costs of land vary between 20 $/ha/yr (2009) for agricultural land uses depending on locations (CPI, 2009).
Labour	Minimum wage is 0.3 $/h in the agricultural sector
Diesel	36 l per ha at cost of 1.02 $/l
Seeds	1333 plants per ha at cost of 0.20 $/plant
Herbicides	3 l/ha at costs of 2.23 $/l
Pesticide	0.1 kg/ha of fungicides and 0.6 l/ha of pesticides at average cost of 9.55 $/l
NPK	60 kg/ha of N fertiliser, 23 kg/ha of P fertiliser and 48 kg/ha of K fertiliser at average cost of 0.77 $/kg

Table C10
Fertiliser requirements for eucalyptus production in Brazil by land suitability.

Required fertiliser amounts (kg/ha)	Suitable	Less suitable
NH_4	83	60
P_2O_5	32	23
K_2O	67	48
CaO	97	70
Total	279	201

Table C11
Value of cost item for eucalyptus production in Brazil.

Cost item	Value	Unit	Source
Wages-field workers	2.87–7.74	$/h	Calculated
Tractor	13.13	$/h	[109]
Fencing-material and machinery	439.17	$/ha	[110]
Plant costs	0.07	$/plant	Various, own calculations
Herbicides	126	$/ha	[110]
Fertilisers	68.6–207.2	$/ha	Various, own calculations
Pesticides chemicals	8.4	$/ha	[110]
Fungicides chemicals	4.2	$/ha	[110]
Land rent	49–145.6	$/ha	World Bank
Harvester[a]	494	k$/machine	[111]
Harvesters – loader[b]	165	k$/machine	[111]

[a] 173 kW John Deere 1270C harvester with a felling processing head JD 762C for felling and bunching trees.

[b] 132 kW Forest loader OP T80 to assist harvester in tree bunching.

Table C12
Poplar SRC yields and fertiliser inputs in Ukraine by land suitability classes.

	Suitable	Marginally suitable
Yield (t_{dm} ha^{-1} yr^{-1})	14	6
NH_4 input (kg/ha)	71	34
P_2O_5 input (kg/ha)	20	10
K_2O input (kg/ha)	52	24
Manure (organic fertiliser equivalent[a]) (tons/ha)	20	11

[a] According to SEC Biomass [97] manure is used instead of chemical fertilisers and estimates are based on a range of 11–40 tons per hectare. Equivalent chemical fertilisers are estimated by [34].

Table C13
Cost assumptions of key switchgrass production inputs in Argentina [44].

Item	2020	2030	Units
Land rent	110	110	$/ha/yr
Seeding input	22.5	22.5	$/ha
Fertiliser input	12.0	49.5	$/ha
Herbicides input	2.85	6.41	$/ha
Labour costs	295.87	552.04	$/ha
Fixed costs machinery	1964	2015	$/ha
Fuel costs	493.11	688.30	$/ha
Aggregate costs	306	373	$/ha

Table C14
Cost estimates of wheat straw collecting and packaging in Ukraine [97].

Straw harvesting activity	Tractor		Fuel		Labour	
	$/ha	$/h	$/ha	$/h	$/ha	$/h
Cutting and raking	35	97	35	100	0.4	1
Baling (square baler + tractor) Bales 30 kg	20	33	14.5	25.2	0.58	1
Forwarding to roadside (500 m)/baler pick up (tractor front end loaders)	20	40	10	22	0.48	1

Table C15
Key assumptions for biomass transportation in selected countries.

	Mozambique	Brazil	Ukraine	Argentina/China
Distance from farm to conversion plant (km)	100	200	50	120
Truck capacities (tons)	20	40	40	40

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